AD/A-006 869

THE JOINT NOL/RAE/WRE RESEARCH PROGRAM
ON BOMB DESIGN. PART IV. THE EXTERIOR
BALLISTICS OF BOMB DESIGN

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White Oak, Maryland

1 December 1974

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NOLTR 74-58	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER AD/A-006869
4. TITLE (and Subtitle) THE JOINT NOL/RAE/WRE RESEARCH PROGRAM ON BOMB DESIGN, PART IV THE EXTERIOR BALLISTICS OF BOMB DESIGN		5. TYPE OF REPORT & PERIOD COVERED
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) F. J. Regan (WOL) J. H. W. Shannon (WRE) F. J. Tanner (RAE)		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Surface Weapons Center White Oak Laboratory Silver Spring, Maryland 20910		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS A320-320C/WF32-323-201
11. CONTROLLING OFFICE NAME AND ADDRESS		12. REPORT DATE 1 December 1974
		13. NUMBER OF PAGES 48
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)
Bombs
Free-Fall Stores
Freely Spinning Stabilizers
Low Drag

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)
Since 1964 extensive and successful collaboration in a bomb dynamics program has continued between research organizations in Australia, the United Kingdom and the United States. Various aspects of this joint effort have been reported in detail in separate reports: Part I treated the dynamics, aerodynamics and performance of free-fall weapons stabilized by fixed cruciform stabilizers. Part II gave a similar treatment of split-skirt (over)

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S/N 0102-014-6601 |

stabilizers.   Part III reviewed results obtained from the use
of freely spinning panel stabilizers.   This series of reports
is concluded in the present document which discusses the task
of the ballistician in light of the knowledge gained during
the program and illustrates the application of the techniques
derived to missile design.   In addition, brief reference is
made to a number of research projects which have stemmed from the
original tripartite work.

NOLTR 74-58   1 December 1974

THE JOINT NOL/RAE/WRE RESEARCH PROGRAM ON BOMB DESIGN,
PART IV   THE EXTERIOR BALLISTICS OF BOMB DESIGN

The purpose of this report is to summarize the tripartite cooperative
free-fall research effort among the Naval Ordnance Laboratory (NOL -
now the White Oak Laboratory (WOL) of the Naval Surface Weapons
Center), the Royal Aircraft Establishment (RAE), and the
Australian Weapons Research Establishment (WRE). This document
is the fourth and last in a series of reports which summarize
various aspects of the program. Of consideration here are some
of the conclusions in the exterior ballistics of bomb design
reached as a result of this joint effort.

This project was sponsored by the Naval Air Systems Command under
AIRTASK No. A320-320C/WF32-323-201.

                              ROBERT WILLIAMSON II
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                              Commander

                              [signature]
                              LEON H. SCHINDEL
                              By direction

CONTENTS

ILLUSTRATIONS

CONTENTS (Continued

1.0 INTRODUCTION

This report is the fourth and final document of the tripartite free-fall weapons dynamics program. The work originally began in 1960 as a bipartite cooperative venture between the United Kingdom and Australia. The main aim was to study the dynamic behavior of free-fall weapons through the complementary use of computer trajectory simulations based upon wind-tunnel data and instrumented free-fall stores. The scope and accomplishments of this early work are presented in detail in reference 1. Technical discussions between representatives of the two countries and the United States research establishments broadened the aims of the program, and since 1964 the program has been pursued on a tripartite basis.

In the context of this report it is appropriate to review briefly the original research program on bomb dynamics and to comment upon the value of the project as a cooperative endeavor between the three participating countries. Timeliness was perhaps a factor which contributed most toward the success of the project because mutual interest in the work was stimulated at the onset through each country's need to establish improved design criteria in bomb ballistics. Exchange visits, made early in the program and continued regularly throughout, led to fruitful sharing of data and experience by bringing together experts from numerous research establishments in the three countries.

The possession of full-scale instrumented bomb test vehicles provided an excellent basis for the experimental program which had the following main objectives:

a. To provide a more rigorous check on the validity of current theories by making correlations between the observed behavior of the research vehicle and that predicted from a mathematical model using the most complete sets of wind-tunnel and free-flight data obtainable.

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[1]Rhodes, C. W., and Shannon, J. H. W., "Results and Conclusions of the Joint RAE/WRE Research Program on the Flight Dynamics and Ballistic Consistency of Freely Falling Missiles, Part I, Bombs Stabilized by Fixed Cruciform Fins," RAE TR 65200, Royal Aircraft Establishment, December 1965; also WRE Report HSA 20, Weapons Research Establishment, November 1965.

b. To investigate ideas, both theoretically and experimentally which provide solutions to some of the stability problems experienced by free-fall weapons or to increase weapon versatility and ballistic consistency through design improvements.

c. To develop new experimental methods for obtaining aerodynamic data.

The first objective is the most important single aspect of the tripartite program. Certainly the most significant advances in bomb ballistics over the past 15 years occurred in the development of three main tools: first, large electronic digital computers for carrying out highly detailed weapon simulations; second, transonic wind tunnels with test sections of sufficient size for testing large-scale models up to one-half scale in this program; and third, reliable full-scale stores with internal instrumentation, together with a telemetry system for transmission of the measured variables to a ground station.

With the availability of these tools among the three countries a meaningful tripartite research program became possible. Extensive wind-tunnel measurements were carried out in laboratories in the United Kingdom and the United States, with some specialized studies being carried out in Australia as well. Trajectory simulations for the research program were performed at the United States Naval Surface Weapons Center, White Oak Laboratory (WOL), and the Australian Weapons Research Establishment. The free-fall telemetry tests were designed and executed by the Weapons Research Establishment.

As noted in b. above, attention was given to the testing of novel stabilizers. Among such devices was the split-skirt stabilizer. A split-skirt stabilizer is formed by slicing the tail cylinder axially into petals, usually four in number. The main advantage of such a stabilizer is its use as a variable drag device, permitting the operation of a free-fall weapon in a high- or low-drag mode by varying the petal opening. The second tripartite report then was devoted to a comprehensive assessment of the aeroballistic characteristics of the split skirt[2]. Another innovative stabilizer was the freely spinning stabilizer. In its simplest form this stabilizer is a conventional panel stabilizer which can rotate about the weapon's longitudinal axis. Rotation of the stabilizer is affected by canting the panels. The forebody will spin only under the influence of its own asymmetries and any torque transmitted from the tail through bearing drag. The advantages of this stabilizer are the minimization or elimination of roll-induced forces and moments, rapid spin

[2]Regan, F. J., Shannon, J. H. W., and Tanner, F. J., "The Joint NOL/RAE/WRE Research Program on Bomb Dynamics, Part II, A Low-Drag Bomb with Split-Skirt Stabilizers," NOLTR 69-232, Naval Ordnance Laboratory; TR 70038, Royal Aircraft Establishment; Report HSA 26, Weapons Research Establishment, November 1969

acceleration of the stabilizer through resonance, and its use as an environmental sensor. The dynamic and aerodynamic characteristics and the anticipated performance of free-fall weapons using the freely spinning stabilizer are reported in reference 3.

Objective c., for the most part, covers various testing techniques whose development was strongly motivated by the tripartite program. Among such improvements in obtaining aerodynamic data might be included the development of gas bearings for pitch damping supports,[4] Magnus balances,[5] electromagnetic transducers for angular measurements in pitch damping,[6] one-, three-, and six-degree-of-freedom data-reduction programs,[7] and various trajectory programs.[8,9]

The present document considers various aspects of the research work not covered in the previous reports. Among these items is the anomalous roll behavior caused by the presence of a yaw probe at the bomb vertex. In addition, a summary is given of various completed and continuing research efforts which, while outside of the tripartite program, nevertheless show the strong influence of the program.

[3]Regan, F. J., Shannon, J. H. W., and Tanner, F. J., "The Joint NOL/RAE/WRE Research Program on Bomb Dynamics, Part III, A Low-Drag Bomb with Freely Spinning Stabilizers," NOLTR 73-77, Naval Ordnance Laboratory; TR 73060, Royal Aircraft Establishment; Report 904 (WR&D), Weapons Research Establishment, June 1973

[4]Regan, F. J., and Iandolo, J. A., "Instrumentation, Techniques and Analysis Used at the Naval Ordnance Laboratory for the Determination of Dynamic Derivatives in the Wind Tunnel," NOLTR 66-23, Naval Ordnance Laboratory, August 1966

[5]Regan, F. J., and Horanoff, E. V., "Wind Tunnel Magnus Measurements at the Naval Ordnance Laboratory," AIAA Paper 66-753, AIAA Aerodynamic Testing Conference, Los Angeles, California, 21-23 September 1966; also AIAA Journal, Vol. 5, No. 6, 1967

[6]Regan, F. J., Ogan, R., and Holmes, J. E., "Variable Reluctance Transducer for Use in Wind Tunnel Pitch-Damping Measurements," NOLTR 65-9, Naval Ordnance Laboratory, 1965

[7]Knadler, C. E., "A Method for Determining the Parameters of Ordinary Differential Equations," NOLTR 68-192, Naval Ordnance Laboratory, November 1968

[8]Holmes, J. E., "A Powered Six-Degree-of-Freedom Trajectory Program for Vehicles with Freely Spinning Tail Stabilizers," NOLTR 69-155, Naval Ordnance Laboratory, October 1969

[9]Goodale, P. L., "An IBM 7090 Six-Degree-of-Freedom Rigid Body Trajectory Program," Tech. Note HSA 118, Weapons Research Establishment, June 1966

Such works include a study of the effect of nose vanes for diminishing the Magnus moment on a free-fall store, and an investigation of the application of freely spinning stabilizers to a canard controlled air-to-air missile.

Broadly, the overall aim of the tripartite program was the improvement of performance and ballistic consistency of free-fall weapons. Thus, a brief outline is included in this report of the significant problem areas of free-fall weapon design. These areas are isolated and identified graphically as functions of static pitch frequency and spin rate. A typical medium-weight free-fall store will then be chosen as a generic weapon in tracing out acceptable design procedures. Finally, the tripartite program will be reviewed with particular emphasis on the effectiveness of such a cooperative effort.

SYMBOLS

A	aspect ratio, b^2/S
b	stabilizer span
$\bar{b}$	stabilizer span in calibers, b/d
C_l	roll moment coefficient, M_x/QSd
C_{l_p}	damping-in roll derivative, $\partial C_l/\partial \hat{p}$
C_{l_δ}	rolling moment derivative due to fin cant, $\partial C_l/\partial \delta$
C_m	pitching moment coefficient, M_y/QSd
C_{m_α}	pitching moment derivative with respect to angle of attack, $\partial C_m/\partial \alpha$
$C_{m_q} + C_{m_{\dot\alpha}}$	damping-in pitch derivative, $\partial C_m/\partial \hat{q} + \partial C_m/\partial(\dot\alpha d/2V)$
C_N	normal force coefficient, $-F_z/QSd$
C_{N_α}	normal force derivative with respect to angle of attack, $\partial C_N/\partial \alpha$
C_n	yawing moment coefficient, M_z/QSd
$C_{n_{p\alpha}}$	Magnus derivative, $\partial^2 C_n/\partial \hat{p}\partial\alpha$
$C_{n_r} - C_{n_{\dot\beta}}$	damping-in yaw derivative, $\partial C_n/\partial \hat{r} + \partial C_n/\partial(\dot\beta d/2V)$
d	reference length (maximum body diameter)
f_R	fineness ratio, l/d

4

$\{F_x, F_y, F_z\}$	forces along $\{x,y,z\}$ axes
I_x	axial moment of inertia
I_y	transverse moment of inertia
K_A	nondimensional axial radius of gyration, $\sqrt{I_x/md^2}$
K_T	nondimensional transverse radius of gyration, $\sqrt{I_y/md^2}$
ℓ	body length
ℓ_T	stabilizer moment arm (calibers)
$\{M_x, M_y, M_z\}$	moments about $\{x,y,z\}$ axes
m	mass
$\{p,q,r\}$	angular rates about the $\{x,y,z\}$ axes
$\hat{p}$	nondimensional spin rate, $pd/2V$
$\hat{q}$	nondimensional pitch rate, $qd/2V$
q	dynamic pressure, $1/2\rho V^2$
$\hat{r}$	nondimensional yaw rate, $rd/2V$
S	reference area, $\pi d^2/4$
S_g	gyroscopic stability parameter
V	airspeed
$\{x,y,z\}$	aeroballistic body axes
α	angle of attack
β	angle of yaw
δ	fin-cant angle
λ	damping factor
ζ	axial-to-transverse inertia ratio
ρ	density
τ	$[1 - 1/S_g]^{-1/2}$
ω_α	circular pitch frequency
$\hat{\omega}_\alpha$	nondimensional pitch frequency, $\omega_\alpha d/2V$

ω_β circular yaw frequency

$\hat{\omega}_\beta$ nondimensional yaw frequency

Subscripts

b   body

n   nutational

p   precessional

t   trim

2.0 ANOMALOUS ROLL BEHAVIOR

An important finding of the research was concerned with the large effect that apparently small configurational changes have on missile flight performance. This was revealed dramatically by gross alteration in the trajectory of a research store which was fitted with a nose probe.

A nose probe was added to a limited number of the free-fall, M557A research stores in order to improve the accuracy in measurement of yaw. The dimensions and position of this probe are illustrated in Figure 1. Initially it was believed that the presence of the probe would have a negligible effect on the flight performance of the store since the length of the probe was less than 7 percent of the body length and the diameter less than 5 percent of the body diameter. However, in two instances abnormal rolling behavior was observed at high incidence during the first few seconds of fall which could not be explained on the basis of the available induced rolling moment data. An example of measured and predicted roll rates is reproduced from reference 1, in Figure 2.

At the time of the flight trials rolling behavior at large angles of attack was not fully understood, but it was known that vortices shed from the bomb body at high incidence could induce exceptionally strong rolling moments if they passed in close proximity to the stabilizing fins. A series of small-scale smoke-tunnel tests[10] carried out at WRE confirmed the presence of such body vortices and the work of Thomson and Morrison[11,12] has further indicated how the characteristics

[10]Thomson, K. D., "On the Flow Over a Bomb Shape at Large Angles of Incidence," WRE Tech. Memo HSA 137, April 1965

[11]Thomson, D. D., and Morrison, D. F., "On the Asymmetric Shedding of Vortices from Slender Cylindrical Bodies at Large Angles of Attack," WRE Tech. Note HSA 106, May 1965

[12]Thomson, K. D., and Morrison, D. F., "The Spacing, Position and Strength of Vortices in the Wake of Slender Cylindrical Bodies at Large Incidence," WRE Report HSA 25, June 1969; also Journal Fluid Mechanics (1971) Vol. 50, Pt. 4, pp. 751-783
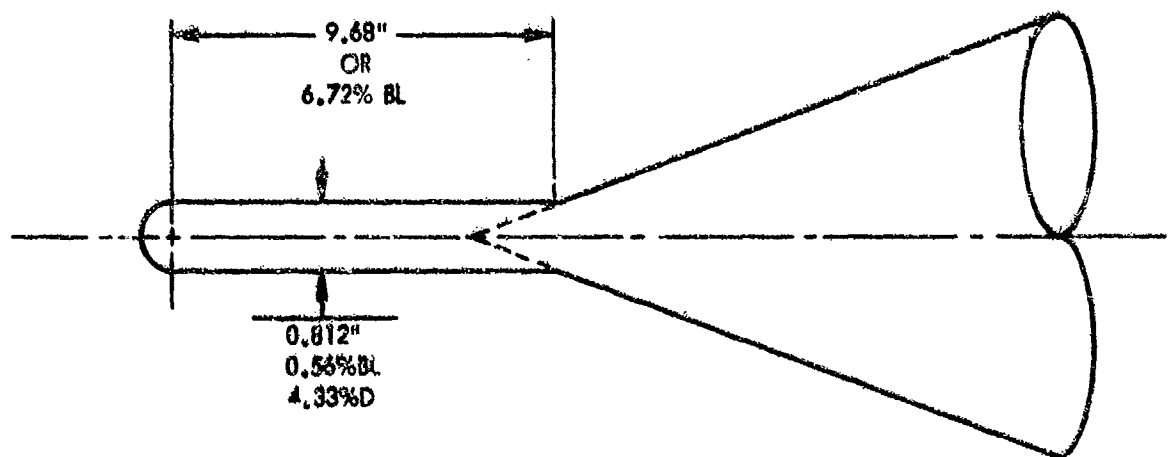
9.68"
OR
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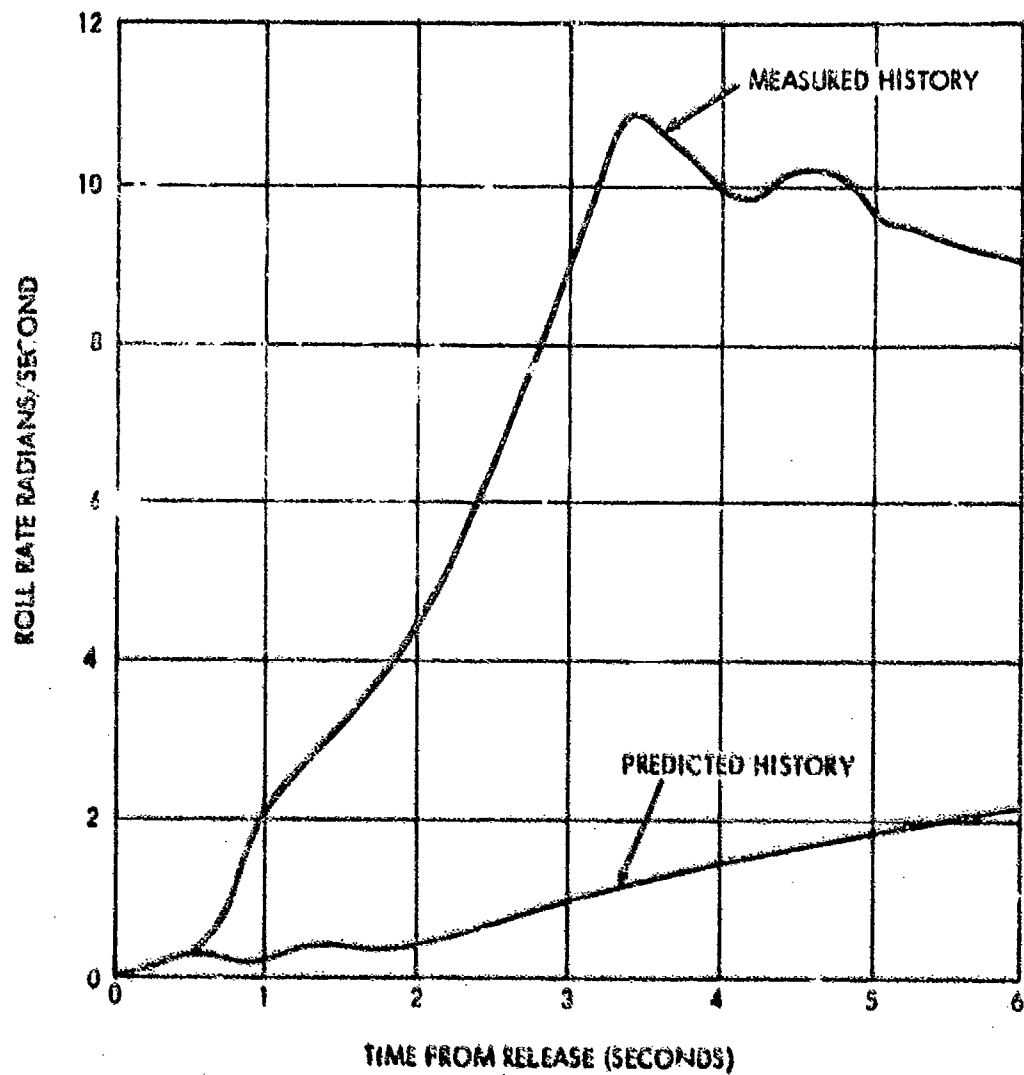0.812"
0.56% BL
4.33% D

FIG. 1 NOSE PROBE GEOMETRY

FIG. 2 COMPARISON OF MEASURED AND PREDICTED ROLL RATES FOR
ROUND NUMBER 726

of such vortices are prone to scale effects and may be critically influenced by extremely small changes in missile nose alignment.

Because wind-tunnel measurements had been carried out on the basic configuration only without the nose probe, it was decided that in view of the evidence available further tests should be made with the nose probe fully represented on the wind-tunnel model. Thus, five-component static measurements were carried out by RAE in the 6- by 8-Foot Wind Tunnel at Farnborough.[13] Comparisons were made at RAE for the model with and without probe, with the probe rotated 180 degrees and at a wide range of Reynolds numbers.

It was found from these data that the normal-force and pitching-moment coefficients were not greatly affected by the presence of the probe. Certainly some alteration of the in-plane force and moment did exist, but not greater than 5 percent in either coefficient at any angle of attack. Clearly, the cause of the abnormal behavior in free fall must have stemmed from those forces and moments which are induced by asymmetries of flow with respect to the plane containing the angle of attack. Upon examination of the side force and yawing moment coefficients it was found that there was a marked difference between the probe and the no-probe configurations especially at angles of attack in excess of 10 degrees. Figures 3 and 4 present the side force and yawing moment coefficients. It is evident that the presence of the probe significantly influences these quantities. The drastic change in the side force and yawing moment with rotation of the probe through 180 degrees is a typical effect of body vortices which are being shed asymmetrically at large angles of attack. This phenomenon was well demonstrated by Thomson and Morrison[10,11] and it arises from a preferred right or left "handing" of the body vortices as determined by the slight but inevitable nose probe misalignment. In Figure 5 similar effects of the nose probe are exhibited by the induced rolling moment coefficient, where rotation of the probe through 180 degrees completely changes the sign of the moment at angles of attack greater than about 12 degrees.

Further study of the probe was carried out by WOL in the Naval Ship Research and Development Center (NSRDC) transonic wind tunnel.[14] This study was concerned with making Magnus measurements on the M823 research store with and without the nose probe. (The M823 configuration is identical with the M557A except for a minor difference in contour of the tail cone which is unimportant in the context of these

[13]Lee, P., and Hacker, I.G., "Induced Rolling Moment Characteristics of the M557 Streamline Bomb at Mach Number 0.5," RAE Tech. Memo Aero 1154, July 1969

[14]Regan, F. J., Holmes, J. E., and Falusi, M. E., "Magnus Measurements on the M823 Research Store with Fixed and Freely Spinning Cruciform Stabilizers, Freely Spinning Monoplane Stabilizers and Split-Skirt Stabilizers," NOLTR 69-214, Naval Ordnance Laboratory, November 1969

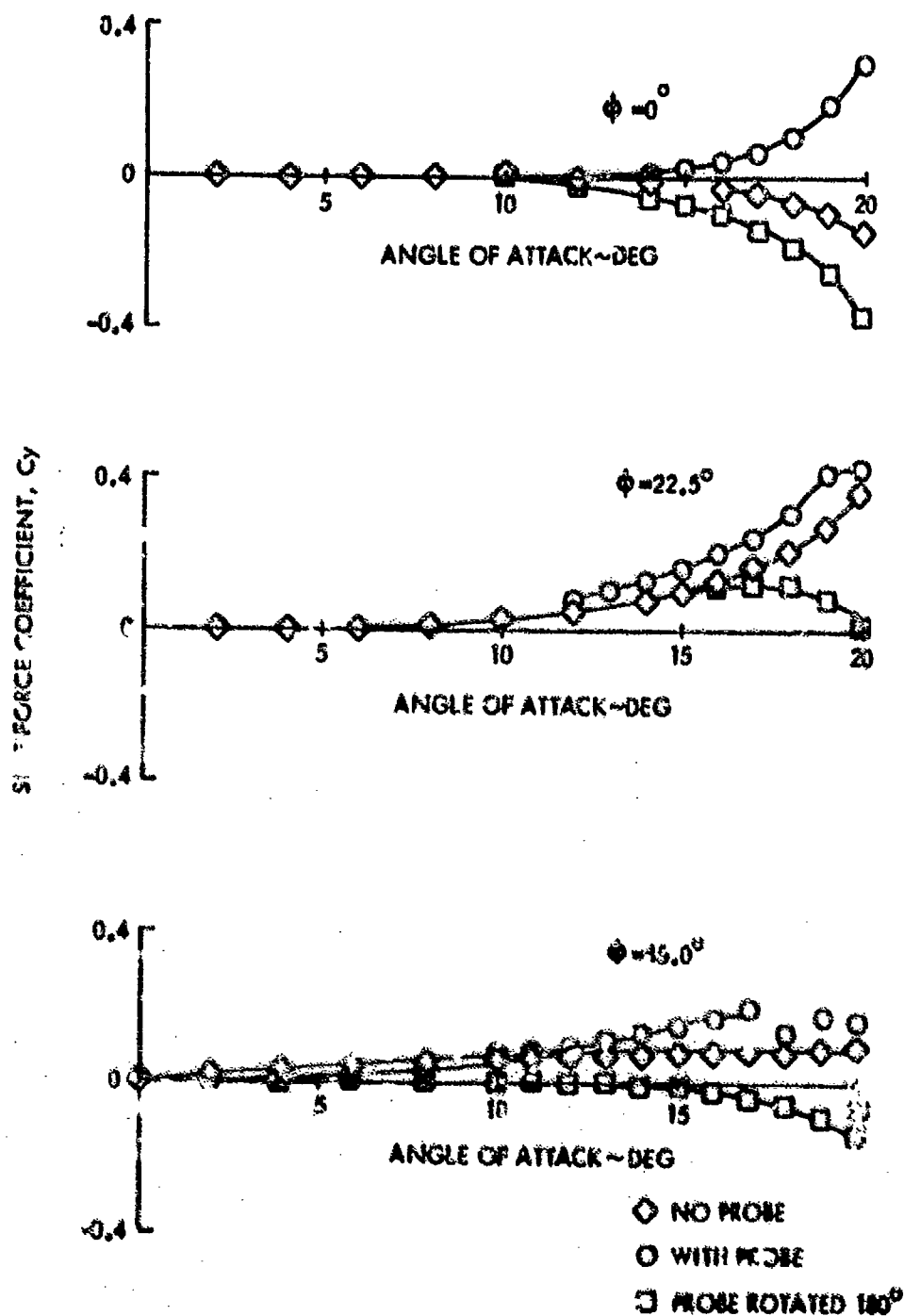FIG. 3 SIDE FORCE COEFFICIENT VERSUS ANGLE OF ATTACK AT A MACH NUMBER OF
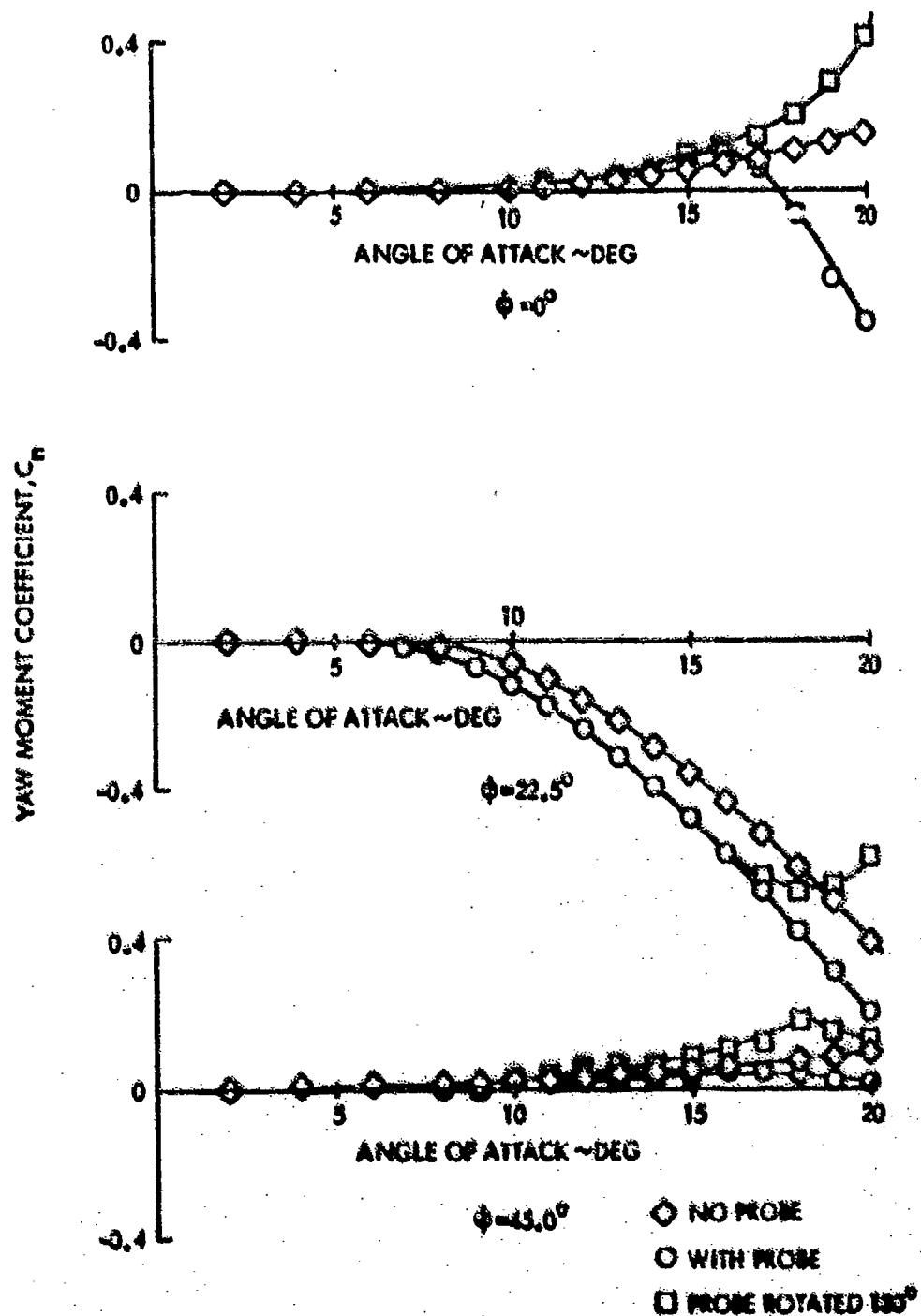0.5 AND A REYNOLDS NUMBER OF 3.33 X 10⁶ PER FOOT

FIG. 4 YAW MOMENT COEFFICIENT VERSUS ANGLE OF ATTACK AT A MACH NUMBER
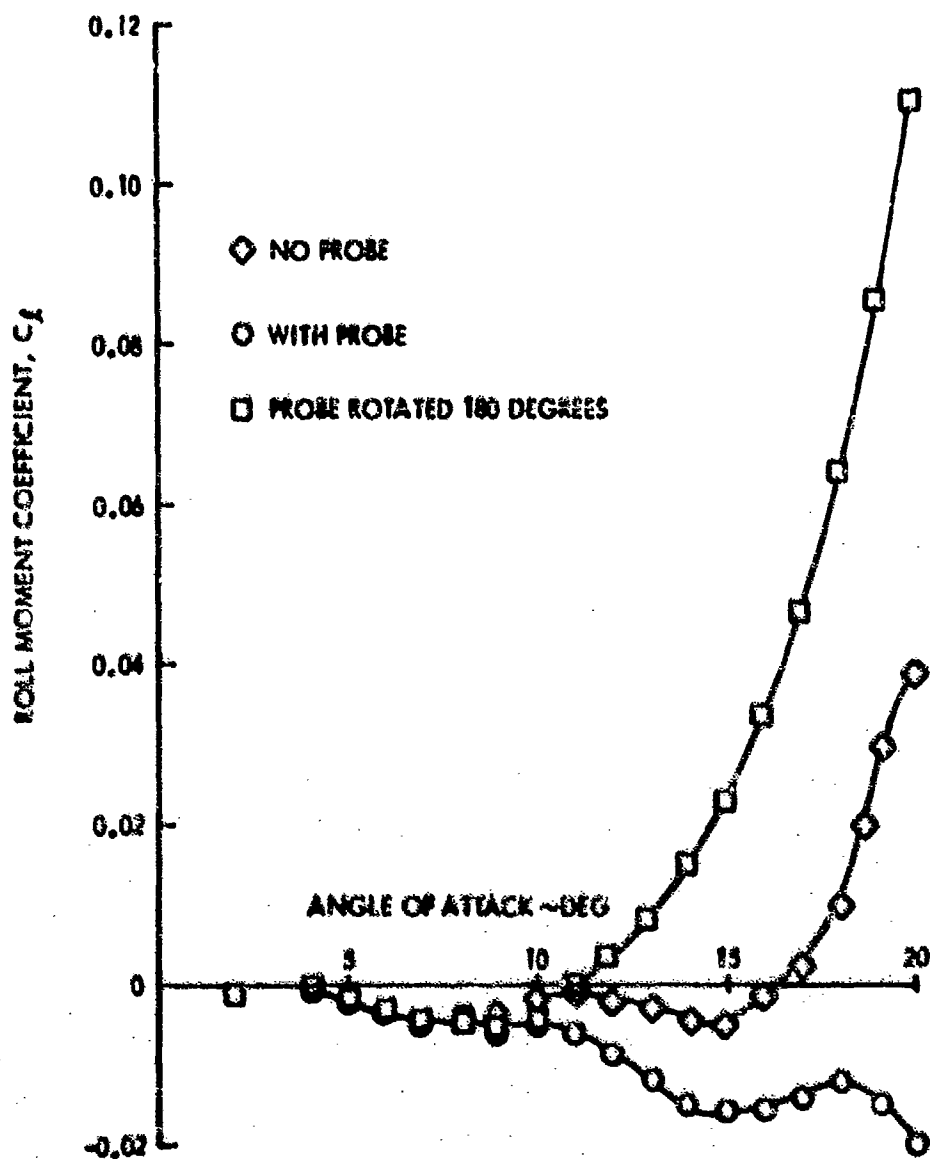OF 0.5 AND A REYNOLDS NUMBER OF 2.33 X 10^6 PER FOOT

FIG. 5 ROLL MOMENT COEFFICIENT VERSUS ANGLE OF ATTACK AT A MACH NUMBER OF 0.9, A REYNOLDS NUMBER OF 3.33 X 10^6 PER FOOT AND AT A ROLL ANGLE OF 22.5 DEGREES

investigations.) Figures 6 and 7 present a portion of the Magnus data obtained. The probe quite clearly causes the sign of the Magnus side force to change. Also it is evident that the probe has an influence at significantly smaller angles of attack on a rotating body.

Recent investigations by Fletcher[15] on the Magnus characteristics of a spinning, inclined ogive cylinder have revealed how the measured side force is critically determined by both the body vortex positions and cross-flow separation positions which can adopt very asymmetric configurations. Using the impulsive flow analogy and a simple potential flow model in conjunction with experimentally determined values for the cross-flow separation angles and the location and strength of the body vortices, Fletcher has demonstrated the full significance of body vortices in their contribution to the Magnus side force. Thus in terms of the impulsive flow analogy the nose probe depicted in Figure 1 has such proportions that, at incidence, a pattern of flow separation would be fully established over its cylindrical surface in advance of the basic body nose-cone. Consequently, flow conditions over the nose-cone would be substantially modified by the probe. It is believed that such flow changes at the nose are sufficient to displace the primary body vortices and alter the overall cross-flow pattern, resulting in the observed differences in side force and yawing moment indicated in Figures 6 and 7.

The result of this investigation provides a major conclusion of the tripartite effort. In unguided free-fall missiles where high angles of attack may be encountered (greater than about 10 degrees), small configurational variations, especially in the region of the nose, can cause drastic changes in the out-of-plane aerodynamic properties of the missile. This conclusion provided some of the motivation to study nose modifications such as the use of nose vanes for controlling the Magnus effect as discussed later in Section 3.0.

3.0 MODIFICATION OF MAGNUS EFFECTS BY NOSE VANES

Further research relating to the original tripartite program was undertaken recently at the Naval Surface Weapons Center, Dahlgren Laboratory (DL).[16] Investigations were made into means by which the precessional damping of the M823 research store might be increased. In studying this problem, an appreciation of the constraints was first obtained from the solution of the linear equations of motion; namely,

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[15]Fletcher, C. A. J., "An Explanation of the Negative Magnus Side Force Experienced by a Spinning, Inclined Ogive Cylinder," WRE Tech. Note 489 (WR&D), November 1971

[16]Becker, M., and Roman, J., "Effects of Nose Vanes on the Dynamic Stability of the M823 Research Bomb," unpublished data from the Naval Surface Weapons Center, Dahlgren Laboratory

FIG. 6 YAW FORCE COEFFICIENT VERSUS REDUCED SPIN RATE FOR THE MK83 RESEARCH STORE WITH FIXED-CRUCIFORM STABILIZER AT A MACH NUMBER OF 0.85 WITH AND WITHOUT A YAW PROBE.

□ WITH PROBE
O WITHOUT PROBE

ANGLE OF
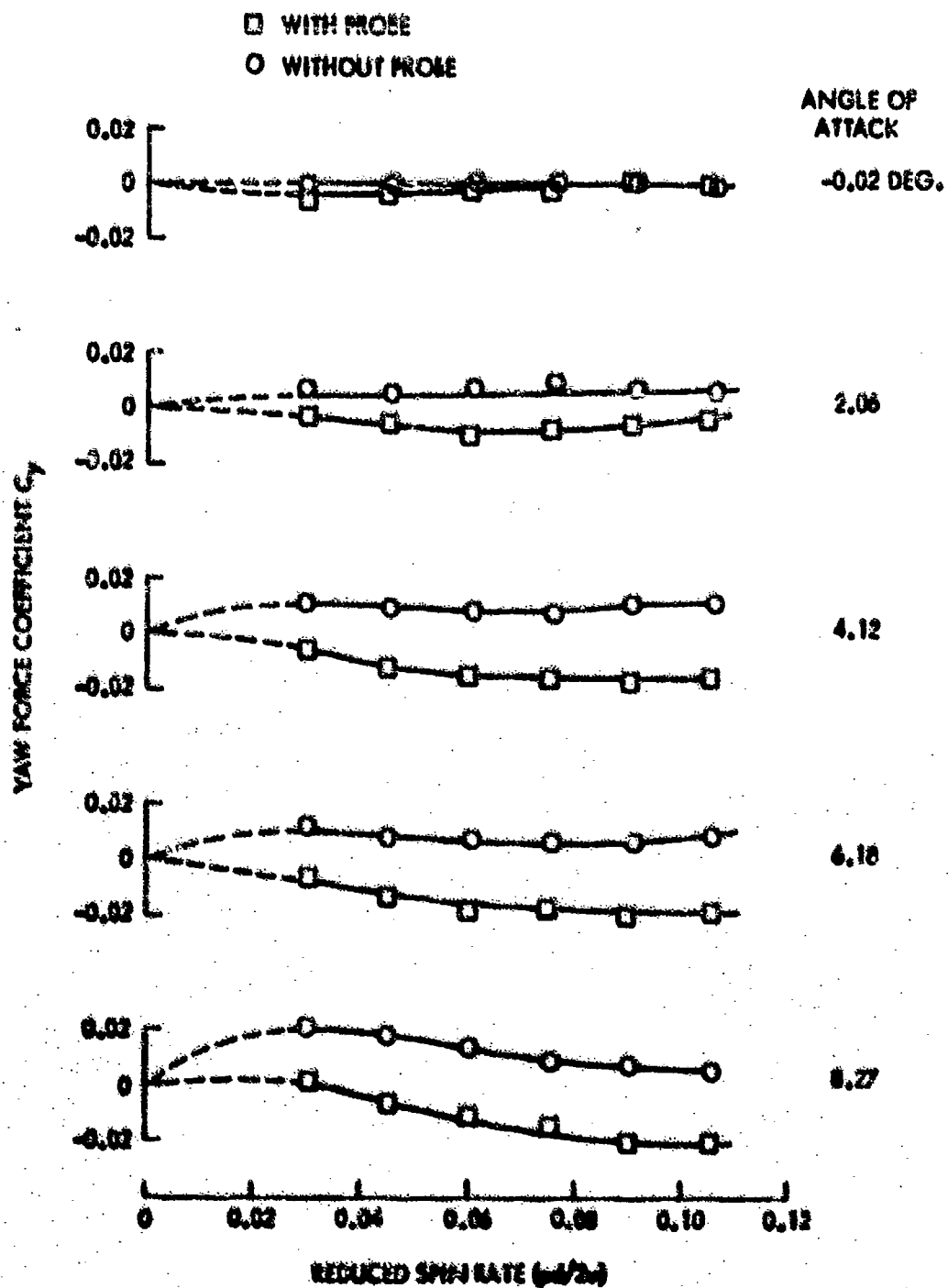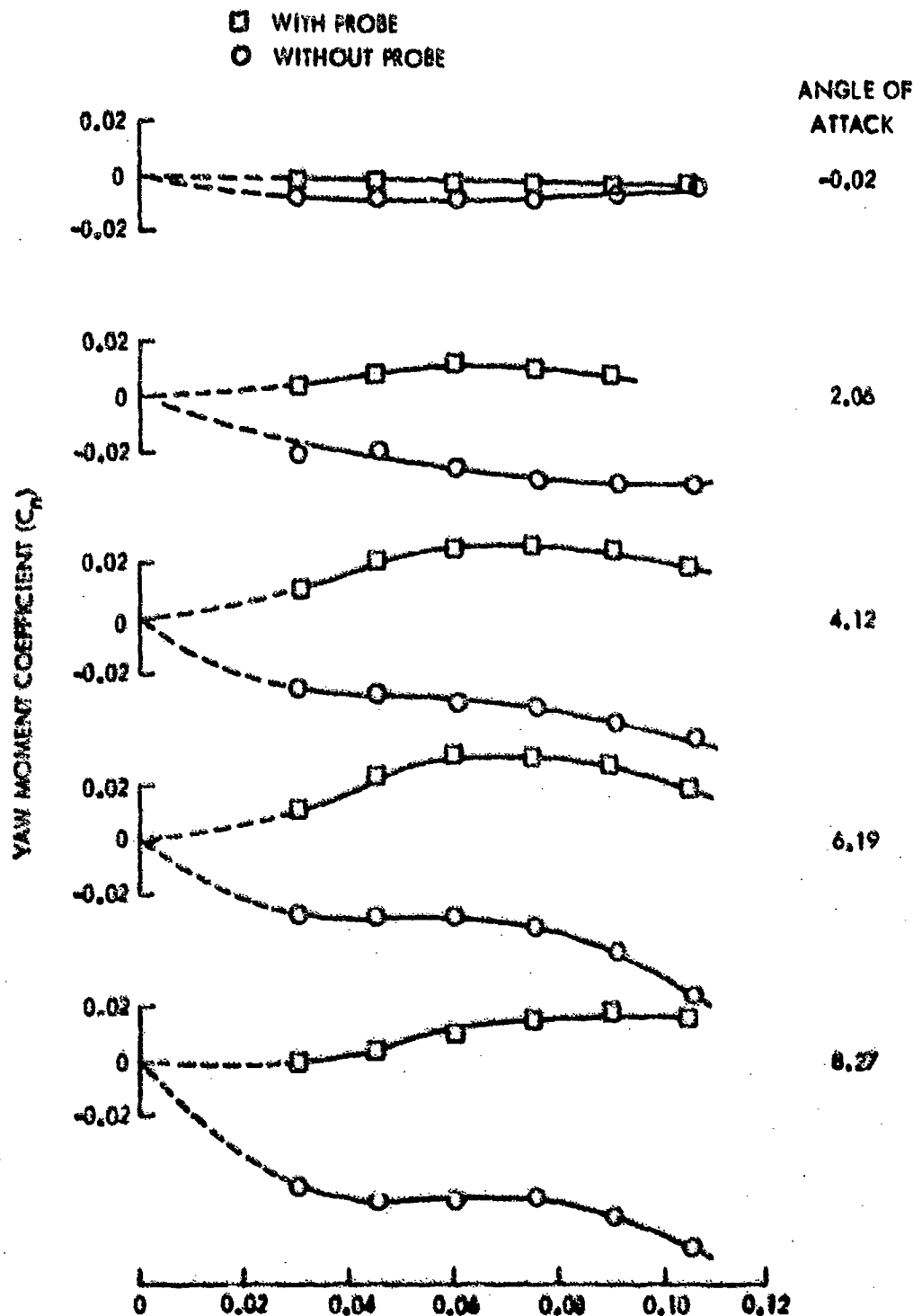ATTACK

-0.02

2.06

4.12

6.19

8.27

FIG. 7 YAW MOMENT COEFFICIENT VERSUS REDUCED SPIN RATE FOR THE M823 RESEARCH STORE
WITH FIXED-CRUCIFORM STABILIZER, AT A MACH NUMBER OF 0.85 WITH AND WITHOUT
A YAW PROBE.

15

$$\bar{\alpha} = \bar{K}_1 e^{(\lambda_n + j\omega_n)t} + \bar{K}_2 e^{(\lambda_p + j\omega_p)t} + \bar{K}_t \tag{1}$$

where $\bar{\alpha}$ is the complex angle of attack, K_1, K_2, K_t are various complex constants, λ_n, λ_p are the damping factors, and ω_n, ω_p, the frequencies of the nutational and precessional modes, respectively. The damping factors, λ_n and λ_p, are of interest in assessing stability and may be written in terms of the aerodynamic derivatives as,

$$\lambda_{n,p} = \frac{QS}{2mV} [C_{N_\alpha} (1 \overset{(-)(+)}{\mp} \tau) + \frac{md^2}{2I_y} (C_{m_q} + C_{m_{\dot\alpha}})(1 \overset{(-)}{\pm} \tau) \overset{(+)}{\pm} \frac{md^2}{I_x} C_{n_{p\alpha}} \tau] \tag{2}$$

where

$$\tau = \frac{1}{(1 - \frac{1}{Sg})^{1/2}}$$

and

$$\frac{1}{Sg} = \frac{4 I_y SQd C_{m_\alpha}}{I_x^2 p^2}$$

The necessary and sufficient condition for the store to be dynamically stable is for $\lambda_n < 0$ and $\lambda_p < 0$. It will be noted in Equation (2) that the signs of the various factors have been indicated. There are three options available to the designer in altering the nutational and precessional damping aerodynamically: change the normal force derivative, C_{z_α}, the damping-in pitch derivative, $C_{m_q} + C_{m_{\dot\alpha}}$, and the Magnus derivative, $C_{n_{p\alpha}}$. However, C_{z_α} cannot be altered without changing the static and, hence, pitch frequency characteristics of the weapon. The relationship between resonance and pitch frequency dictate that the normal force coefficient, C_{z_α}, cannot be readily changed. In addition, configurational changes that would alter the damping-in pitch derivative, $C_{m_q} + C_{m_{\dot\alpha}}$, would almost certainly affect the pitch frequency. The third term, identified as the Magnus moment derivative, $C_{n_{p\alpha}}$, offers the only hope of altering the damping factors without at the same time causing unacceptable changes in the static characteristics of the weapon.

It will be noted in Equation (2) that the Magnus derivative has a damping effect on one mode and an undamping effect on the other, regardless of the sign of the derivative. Thus, the Magnus effect increases damping of the precessional mode and undamps

the nutational mode (if $C_{n_{p\alpha}}$ is positive) or increases damping of
the nutational mode and undamps the precessional mode (if $C_{n_{p\alpha}}$ is
negative). In Equation (2) the term containing the damping-in pitch
derivative, $C_{m_q} + C_{m_{\dot\alpha}}$, dominates the static force term, C_{z_α}.
Accepting this simplification it may be seen that the precessional
damping is more critical because the multiplier $(1 - \tau)$ is smaller
for the precession mode. Since a negative Magnus moment derivative,
$C_{n_{p\alpha}}$, was measured, clearly any attempt to diminish this quantity
will aid precessional damping. Of course, reducing the magnitude of
$C_{n_{p\alpha}}$, or even causing it to become positive, will decrease
nutational damping, but, as pointed out above, the situation here
is less critical.

The Dahlgren Laboratory investigation involved placing nose
vanes on the M823 research store in an attempt to make beneficial
changes to the Magnus moment derivative. The vanes were canted at
+15 and -15 degrees relative to the body center line. Vanes at
the positive cant angle are illustrated in Figure 8. Tests were
conducted by the Dahlgren Laboratory at the Arnold Engineering
Development Center at seven Mach numbers (0.2 to 1.2) and at angles
of attack varying from -2 to +16 degrees. The model was driven in
spin by means of fins canted at angles from 1 to 5 degrees. In
these tests the model was mounted on a conventional Magnus balance
which provided four-component data: side force, yawing moment,
normal force and pitching moment.

Based on the above tests it was found that the nose vanes caused
a significant alteration in the Magnus characteristics of the M823
research store at transonic speed. The negatively canted vanes
(-15 degrees) caused an increase of the Magnus force in the negative
direction compared with the force measured on the base configuration
(no vanes). From Equation (2) it may be seen that an increasingly
negative Magnus moment derivative results in a decrease in preces-
sional stability and an increase in nutational stability. Since
precessional stability is more critical, the vanes set at -15 degrees
result in a decrease in weapon performance. The positively canted
vanes, on the other hand, were found to reduce the magnitude of the
negative Magnus moment and, in some cases, to cause the sign of
$C_{n_{p\alpha}}$ to become positive.

As pointed out above, only four-component data were obtained
in these tests, i.e., the drag coefficient, C_D, and the damping-in
pitch derivative, $C_{m_q} + C_{m_{\dot\alpha}}$, were taken from earlier tripartite work.
The assumption was made that the presence of either set of nose vanes
had negligible effect on the drag and on the damping-in pitch
derivative. Using Equation (2) in concert with a roll equation to
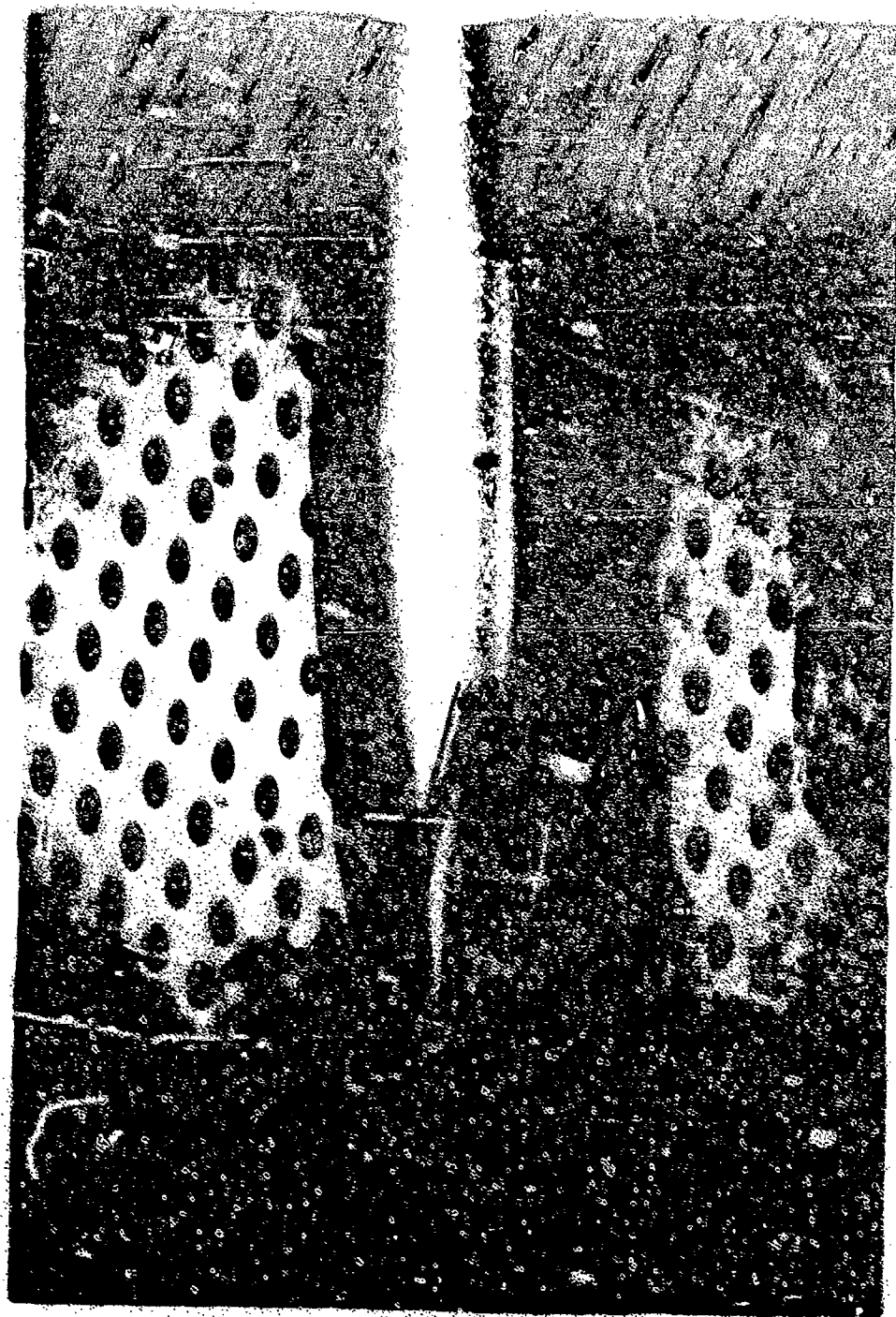generate spin rate, p, and a particle trajectory program to provide

17

FIG. 8 BOLT BREAKUP STORE WITH NOSE VANES

airspeed and Mach number, it was possible to compute the damping factors for several launch conditions. Figures 9 and 10 present a comparison between the two vanes and the basic body on the basis of the nutational and precessional damping, respectively. In these figures the bomb was launched at 600 knots from an altitude of 30,000 feet. The fin-cant angle was 3 degrees. It may be seen that the +15-degree vane results in considerably less nutational damping than either the -15-degree vane or the basic configuration. However, in the more critical precessional mode, the +15-degree fin vane markedly improves the damping. The -15-degree vane is totally unacceptable since it undamps the precessional mode for most of the flight.

One of the more interesting aspects of this investigation is the determination of the Magnus derivative, $C_{n_{p\alpha}}$. In reference 17 the position was taken that the Magnus forces and moments were identified entirely with the side force and yawing moment. However, to use these data in a linear stability analysis (Eq. (2)) it was necessary to determine the Magnus moment derivative, $C_{n_{p\alpha}}$. A bivariate least-squares fitting technique was used to fit the side force and yawing moment data as a function of angle of attack and reduced spin rate. The minimum degree polynominal which provided a satisfactory fit is the following for the Magnus moment,

$$C_n = C_0 + C_{11} \, \hat{p}\alpha + C_{31} \, \hat{p}^3\alpha + C_{13} \, \hat{p}\alpha^3 + C_{33} \, \hat{p}^3\alpha^3 \tag{3}$$

where $\hat{p}$ is the reduced spin rate and α the magnitude of the angle between the zero-lift line of the model and the free-stream flow. The constant, C_0, is an indicator of the experimental bias and is, of course, excluded from the stability analysis. Clearly the term, C_{11} is identical to the linear Magnus derivative, $C_{n_{p\alpha}}$, as may be seen by taking the first cross derivative. The remaining terms indicate the nonlinearity of the yawing moment with the $\hat{p}$ and α variables. A nonlinear formulation of the Magnus derivative follows from Equation (3) as

$$C_{n_{p\alpha}} = \frac{C_n}{\hat{p}\alpha} = C_{11} + C_{31} \, \hat{p}^2 \tag{4}$$

17 Regan, F. J., and Falusi, M. E., "The Static and Magnus Aerodynamic Characteristics of the M823 Research Store Equipped with Fixed and Freely Spinning Stabilizers," NOLTR 72-291, Naval Ordnance Laboratory, December 1972
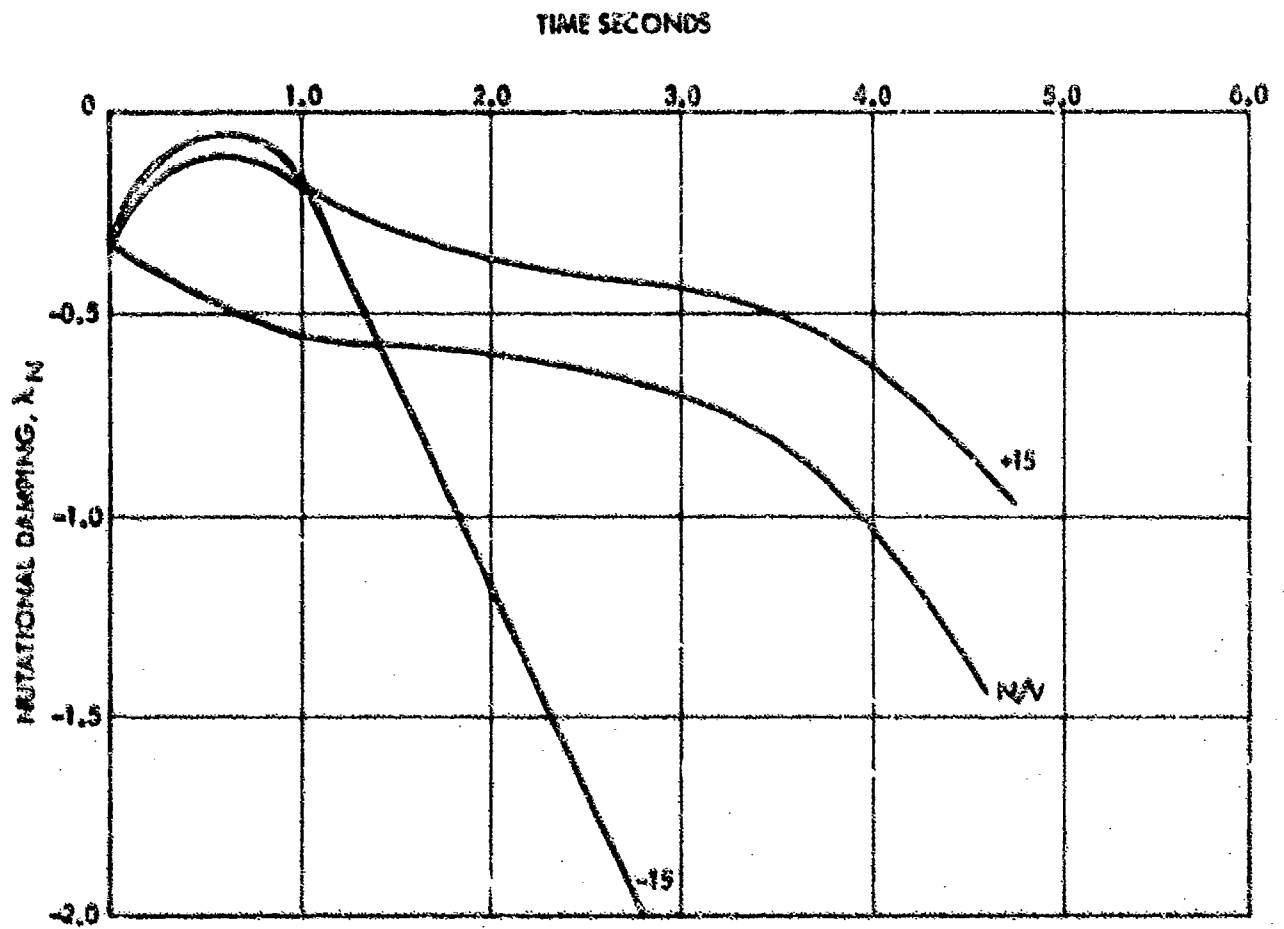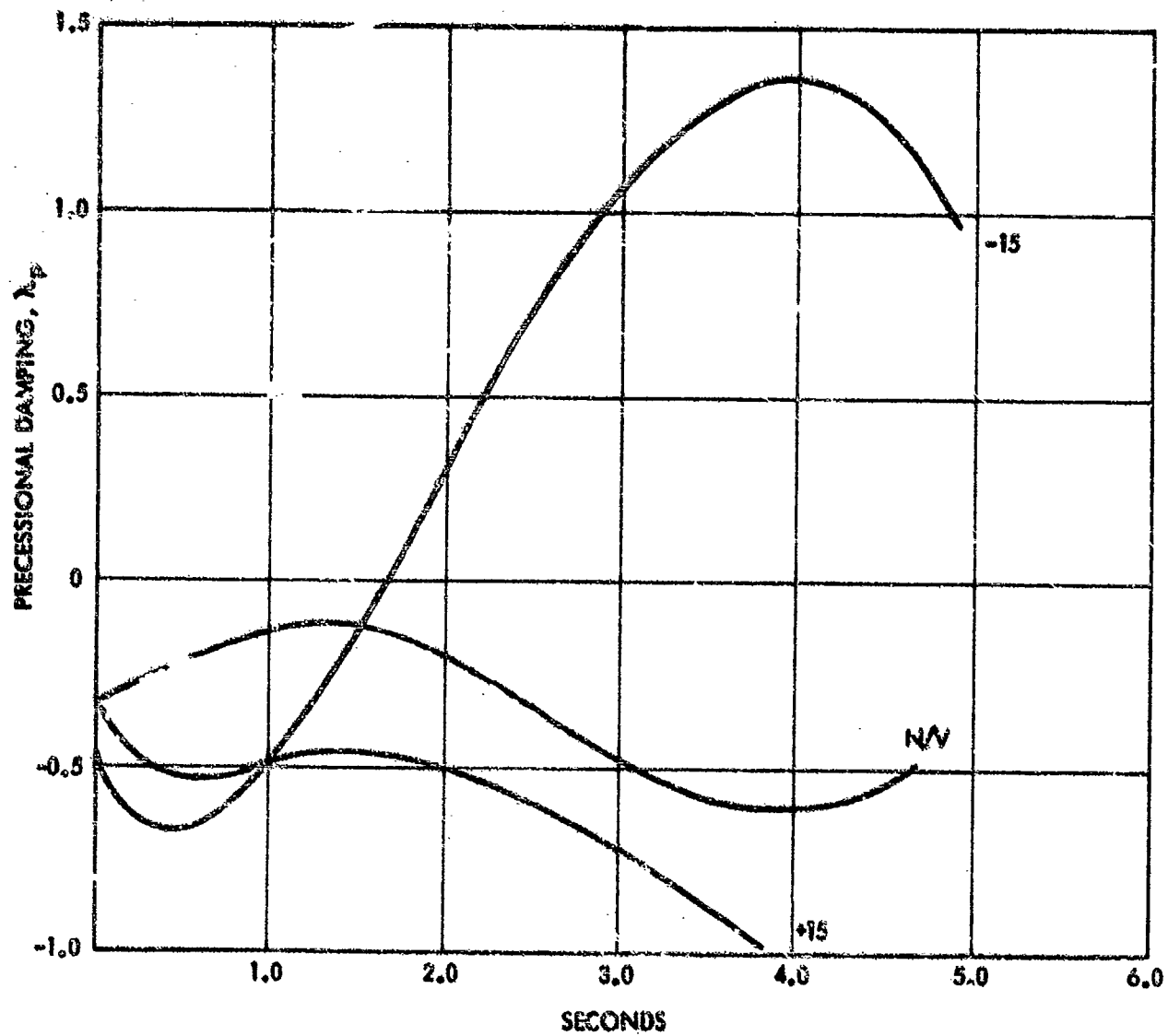
FIG. 9 NUTATIONAL DAMPING VERSUS TIME

FIG. 10 PRECESSIONAL DAMPING VERSUS TIME

In the linear stability analysis (part of the results are presented in Figures 9 and 10) Equation (4) was used for $C_{n_{p\alpha}}$. Thus, a spin rate dependency was introduced into the stability criteria.

Further details of this study of the Magnus moment-altering vanes are given by Becker and Roman.[16]

4.0 OUTLINE OF RELATED RESEARCH

Research in the tripartite program extended over a period of some years, during which time a variety of related work was initiated. Such activities are outlined below.

4.1 Aerodynamics of the Monoplane Tail

Stabilization of the M823 research store by means of a freely spinning monoplane tail, as described in Part III (ref. 3) of the joint program, clearly shows promise for aircraft weapon applications in underwing stowage. Accordingly considerable effort was devoted to wind-tunnel measurements of this configuration (ref. 18, 19 and 20). To allow realistic predictions of flight behavior, detailed information was required defining the static and pitch-damping coefficients as functions of body incidence and stabilizer roll angle. Figure 11, using data from reference 17, illustrates the extent of variation in static margin (moment reference about body's midpoint) experienced with the monoplane tail. Thus, at zero roll angle (fin panels normal to the incidence plane) the static margin is one caliber. At 40-degrees roll angle the configuration is just neutrally stable and at 90-degrees roll angle the overall center of pressure moves progressively forward to about 3 calibers ahead of the body vertex.

The flight dynamics and stability of missiles with freely spinning stabilizers was briefly analyzed in Appendix 1 of reference 3 and is further expanded in reference 21.

[18] Regan, F. J., "Preliminary Static Wind Tunnel Measurements on the M823 Research Store with a Monoplane Stabilizer," private communication, Naval Ordnance Laboratory, January 1971

[19] Marsden, P., "Results of Wind Tunnel Tests on the M823 Research Store with Fixed Monoplane Fins (ARA Model M23)," ARA Model Test Note M25/1, Bedford, UK, 1967

[20] Wingfield, J. G., "Results of Wind Tunnel Tests on the M823 Research Store with Fixed Monoplane Fins (ARA Model M25)," ARA Model Test Note M25/2, Bedford, UK, December 1968

[21] Regan, F. J., "Static and Dynamic Stability of Free-Fall Stores with Freely Spinning Stabilizers," NOLTR 73-19, Naval Ordnance Laboratory, January 1973
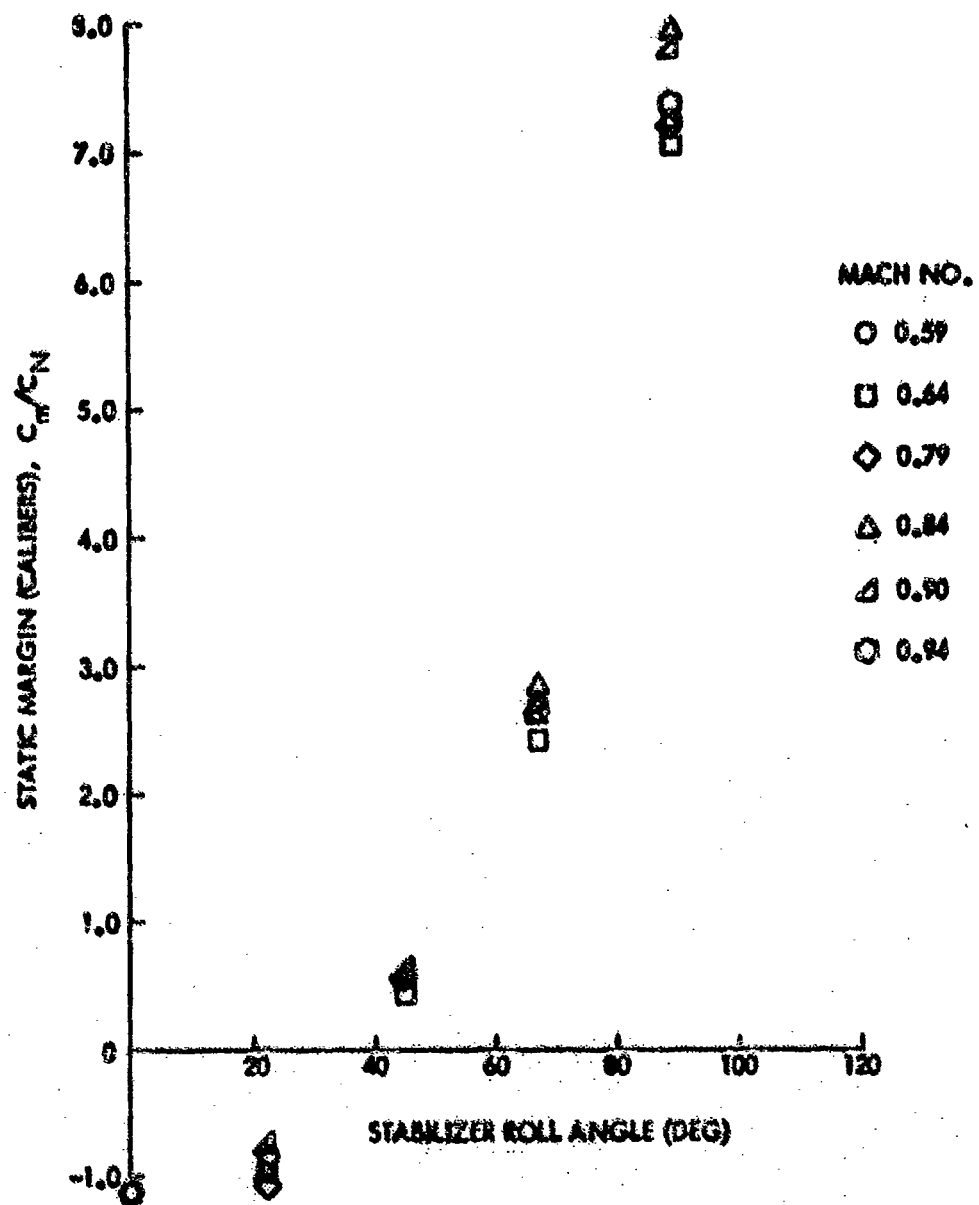
FIG. 11 STATIC MARGIN VERSUS STABILIZER ROLL ANGLE

4.2 Application of Freely Spinning Stabilizers to Guided Missiles

A potentially very practical application of the freely spinning stabilizer is seen to arise in designing air-to-air guided missiles, where canard control systems are often used. Roll stabilization is extremely difficult to achieve with conventional canard designs because of their downwash effects on the rearward lifting surfaces. This inherent weakness may well be overcome by the freely spinning stabilizer which is not mechanically coupled to the forebody.

Based upon reasoning of this kind Holmes[22] at WOL, has developed a six-degree-of-freedom computer program to simulate the flight performance of powered missiles with freely spinning stabilizers. Such a program may be expected to find many applications in the near future.

4.3 Examination and Measurement of Magnus Effects

An important aspect of the tripartite program was the opportunity it presented for systematically studying the Magnus effect on a finned missile. It has been qualitatively established for many years predating the tripartite research that the Magnus effect could be significant in free-fall missile performance. However, the Magnus force was often tacitly assumed to be linear in effect and entirely viscous in origin. Extensive Magnus measurements on the M823 research store has clearly demonstrated nonlinear variations with angle of attack and lead to the belief that the Magnus contribution from the stabilizer may be explained on the basis of inviscid fluid mechanics.

Beyond the immediate post-launch period, from 1 to 5 seconds depending upon the altitude (i.e., density), the typical free-fall store has a steady state spin rate established uniquely by the angle of fin cant. Thus, if a wind-tunnel model possessing geometrical similarities (including fin cant) to a full-scale weapon is tested at a given angle of attack and Mach number, the reduced spin rate will be that produced by the full-scale weapon at the same Mach number and angle of attack. Since the Magnus effect is defined uniquely by reduced spin rate, angle of attack and Mach number, the wind-tunnel measured aerodynamic coefficients will be appropriate to the full-scale weapon. In other words, after an initial period of spin acceleration, the reduced spin rate is not an independent parameter. If the angle of attack and Mach number are fixed, the reduced spin rate is also fixed (assuming fin cant to be constant). Thus, much of the original Magnus program reported in reference 14 was rerun at the Arnold Engineering Development Center (AEDC). In these latter tests fin cant was used to drive the model rather than an internal electric motor.[17] An important result of this comparative

[22]Holmes, J. E., " A Powered Flight Six-Degree-of-Freedom Trajectory Program for Vehicles with Freely Spinning Tail Stabilizers," NOLTR 69-155, Naval Ordnance Laboratory, October 1969

effort was the conclusion that an erroneous simulation will result
if a model with zero fin cant, say, is spun by a motor to simulate
the spin conditons of a canted fin. In short, the Magnus effect
over most of the weapon's trajectory is simulated adequately by
spinning the model by means of the exact fin cant.

An interesting study which stemmed from the above-mentioned
Magnus testing program was the attempt to predict qualitatively the
Magnus load due to the stabilizer alone through the use of Platou's
qualitative theory.[23] This theory is based upon the alteration of
the stabilizer pressure distribution by means of wake interference
on the stabilizer. In comparison between AEDC measurements and a
formulation of Platou's theory, it appeared that up to 5 degrees
angle of attack the theory was in good agreement with the measured
loads. The result of this work has been presented in reference 24.

5.0 BOMB DESIGN CONSIDERATIONS

5.1 Initial Design Study

The weapon designer is faced with many constraints which combine
to place limitations on the range and even choice of design parameters.
For example, the weapon's overall dimensions must permit carriage
on a variety of aircraft. The diameter is probably fixed to meet
existing carriage requirements. An important parameter in free-fall
dynamics, such as the mass distribution, is severely restricted by
lethality requirements and internal component layout. If the weapon
is to be subjected to external carriage on a high-speed aircraft,
there will be severe restrictions on bluff-nose shapes. Rack and
bomb-bay stowage places further limitations on the allowable tail
length and fin span, possibly necessitating the use of retractable
fins. In the process of complying with these constraints, the
weapon designer can present to the exterior ballistician a fairly
comprehensive sketch of the weapon in the early concept-forming
stages of design.

With such information the ballistician is able to make a
preliminary estimate of the aerodynamic characteristics and, if
necessary, suggest changes in the configuration to ensure that
adequate static stability is obtained. Some compromise between
weapon designer and ballistician is almost inevitably required in
matching the weapon/aircraft interface, and, too frequently, this
produces a weapon design with marginal static stability. At this
stage the aerodynamic estimates must be checked by means of wind-
tunnel tests on the proposed weapon shape. It is important that
the ballistician be acutely aware of the designer's intentions,

[23]Platou, A. S., "The Magnus Force on a Fixed Body," Ballistics
Research Laboratories Report 1193, March 1963

[24]Regan, F. J., "Magnus Measurements on a Freely Spinning Stabilizer,"
AIAA Paper No. 70-559, AIAA Atmospheric Flight Mechanics Conference,
Tullahoma, Tenn., 13-15 May 1970

particularly with regard to changes in external shape which may be caused by small additions, such as lugs, fuzes and sensors. The position of the center of gravity and future aircraft carriage requirements should also be explicitly defined.

5.2 Tasks of the Ballistician

To achieve the desired weapon effectiveness, bombs must give predictable performance and consistent aiming capability without endangering the launch aircraft at release. Factors which the ballistician must consider in this context are the weapon's quick recovery from a release disturbance and freedom from dynamic instabilities during its fall. In addition, he may be required to produce preliminary estimates of impact velocity, time to fall to a specified height and speed at a given altitude. Such information on the flight environment is generally required early in a weapon development program to assist with the design of fuzes, etc.

Consequently, it is necessary for the ballistician to obtain an accurate measure of bomb drag, together with the aerodynamic characteristics which determine flight stability at both small and large angles of attack. In the preliminary stages of development the required aerodynamic characteristics may be estimated by synthesizing component contributions or predicted from available data on similar configurations. Later, when a design is "frozen," wind-tunnel measurements in conjunction with a trajectory simulation program may be used for fairly precise estimates of weapon performance. This latter procedure has been discussed extensively in the preceding reports of this series.[1,2,3] For the present purposes therefore, only the salient features of the flight dynamics envelope will be highlighted.

By means of a simple diagram it is possible to illustrate the regions of stability and instability from which relevant design criteria may be established for a bomb with fixed stabilizers. The two most significant parameters in establishing bomb dynamic performance are the natural pitch frequency and the spin rate. Figure 12 presents a plot of the reduced (natural) pitch frequency versus the equilibrium reduced spin rate.

A simple expression for the reduced spin rate in terms of aerodynamic derivatives and the fin-cant angle follows from an integration of the roll equation of motion which yields the expression,

$$\hat{p} = -\frac{C_{\ell\delta}\delta}{C_{\ell p}} \tag{5}$$

where $C_{\ell\delta}$, $C_{\ell p}$ and δ are the roll-driving moment derivative due to fin cant, the roll-damping moment derivatives and the fin-cant angle, respectively. Thus, for a given configuration, the reduced spin rate, $\hat{p}$, is proportional to the angle of fin cant, δ. It would appear
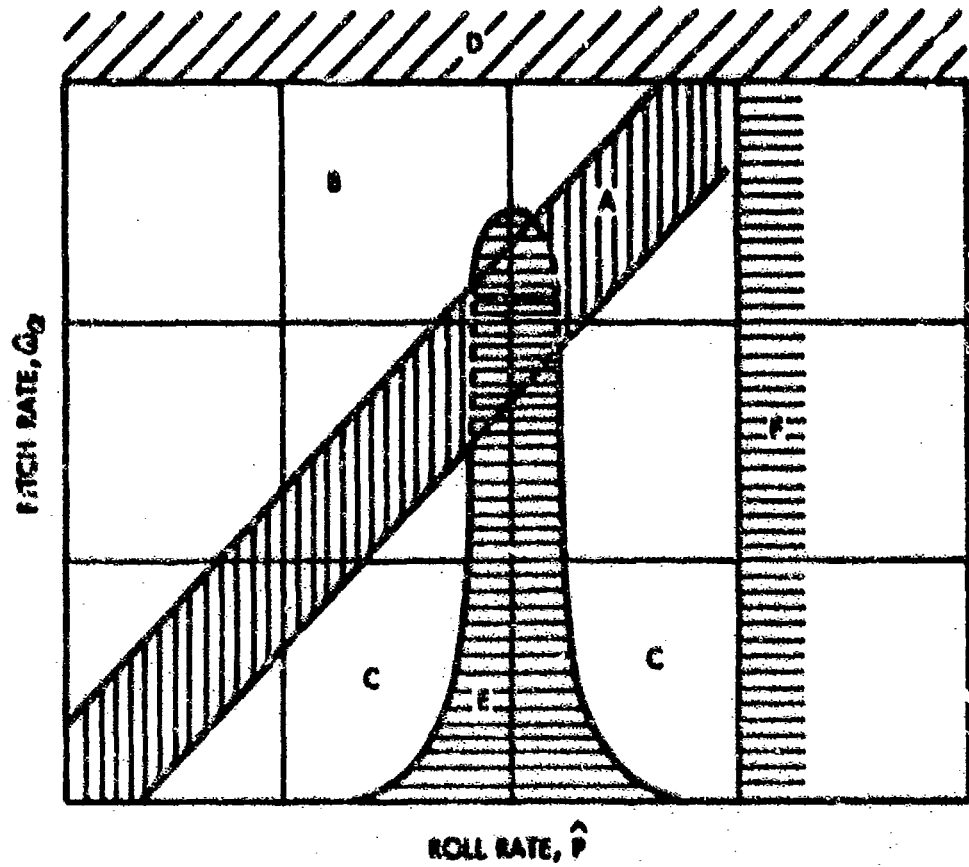
FIG. 12 BOMB STABILITY DESIGN BOUNDARIES

that there is no bound on the upper value that $\hat{p}$ may reach. However, excessively high spin would be limited by aerodynamic effects, such as fin stall, which were not included in the relationships from which Equation (5) was derived. Subsequently, it will be shown that well within the range of small fin-cant angles (less than 4 degrees) the aerodynamic (Magnus) and inertial coupling between yaw and pitch motions puts a practical upper limit on fin cant and, hence, on spin rate.

The pitch frequency, ω_α, may be written as,

$$\omega_\alpha = \sqrt{-\frac{C_{m_\alpha} \rho V^2 S d}{2 K_T^2 m d^2}} \tag{6}$$

where C_{m_α}, ρ, V, S, d, m and K_T are the derivatives of the static pitching moment, the medium density, the free-stream airspeed, the reference area, and reference length, the weapon mass and the transverse radius of gyration (in calibers), respectively. The reduced pitching frequency follows from Equation (6) by expressing the mass, m, as

$$m \approx \rho_b S d f_R$$

where ρ_b is the average density of the weapon and f_R is the fineness (length-to-diameter) ratio. Equation (6) may then be rewritten as,

$$\hat{\omega}_\alpha = \sqrt{-\frac{C_{m_\alpha}}{8} \frac{\rho}{\rho_b} \frac{1}{f_R} K_T^{-2}} \tag{7}$$

Further to this the pitching-moment derivative, C_{m_α}, may be written in terms of the stabilizer normal-force derivative, $C_{N_\alpha}^T$, as

$$C_{m_\alpha} \approx -\frac{4}{\pi} \ell_T \bar{b}^2 \frac{C_{N_\alpha}^T}{\mathcal{A}} \tag{8}$$

where $\bar{b}$ is the span of the tail fins in calibers, ℓ_T, the distance from the weapon center of gravity to the aerodynamic center of the tail, in calibers, and $\mathcal{A}$ the aspect ratio of the tail. Inserting expression (8) into Equation (7) gives

$$\hat{\omega}_\alpha = (\frac{\bar{b}}{K_T}) \sqrt{(\frac{C_{N_\alpha}^T}{2\pi})(\frac{\rho}{\rho_b})(\frac{\ell_T}{\mathcal{A}})(\frac{1}{f_R})} \tag{9}$$

28

In this form Equation (9) clearly indicates the basic parameters which place an upper limit on realizable values of the pitch frequency. Referring to Figure 11, the boundary defined by Equation (9) is represented as a line parallel to the reduced spin rate axis. Pitch frequencies above this boundary, region D, are not realizable because of operational constraints on fin span, fineness ratio, etc.

A further consideration in bomb design is the avoidance of the spin-yaw resonance condition which, according to linear analysis,[25] is associated with amplification of trim in the presence of small configurational asymmetries and this occurs when

$$\frac{\hat{\omega}_\alpha}{\hat{p}} = 1 - \xi \tag{10}$$

where $\xi = (K_A/K_T)^2$ is the ratio of the square of the axial-to transverse radius of gyration. Since this ratio is found to be less than 0.1 for any practical bomb design, a convenient simplification of Equation (10) is

$$\hat{\omega}_\alpha \approx \hat{p} \tag{11}$$

Thus, the resonance condition occurs when the pitch frequency approximately equals the spin frequency. In Figure 12 this condition is represented as a straight line of unit slope. The band (region A) covering this line indicates that resonance may be serious when the spin rate is in the vicinity of the pitch frequency.

An additional area of danger is depicted by region E which is associated primarily with flight behavior at large angles of attack. "Catastrophic yaw" at release is a typical problem occurring in this area and is caused when forces and moments induced at high angles of attack (greater than 15 degrees for a streamlined body) produce a divergence from the disturbance imparted to the missile at release. Another problem can arise where fins are designed deliberately to impart roll. In this case, soon after release, the yaw-induced rolling moment combines with the basic missile-roll characteristics to produce a sustained, large amplitude, lunar motion.

It was mentioned earlier that the presence of Magnus effects restricted the upper bound of spin rate. This may be more clearly appreciated by reference to the solution of the linear equations of motion previously given in expressions 1 and 2. Since the main concern here is with conditions at the upper limit of spin rate, it is possible to simplify expression 2 for the nutational and pre-cessional damping factors by ignoring the term in C_{N_α} and assuming

[25]Nicolaides, J. D., "On the Free Flight Motion of Missiles Having Slight Configurational Asymmetries," BRL Report No. 858, June 1953

$$\tau = (1 - \frac{1}{Sg})^{-1/2} \approx 1 - 2(\frac{K_T}{K_A})^2(\frac{\hat{\omega}_\alpha}{\hat{p}})^2 \qquad (12)$$

because $\frac{1}{Sg} \ll 1$ for large values of $\hat{p}$. Under these conditions the expressions for λ_n and λ_p reduce to

$$\lambda_n = \frac{QS}{2mV} \{K_T^{-2}(C_{m_q} + C_{m_{\dot\alpha}}) + K_A^{-2} C_{n_{p\alpha}}\} \qquad (13)$$

and

$$\lambda_p = \frac{-QS}{2mV} \{K_A C_{n_{p\alpha}}\} \qquad (14)$$

where it has been taken that in the limit as $\hat{p} \to \infty$, $(\hat{\omega}_\alpha/\hat{p}) \to 0$. For the case of nutational damping in expression (13), since $(C_{m_q} + C_{m_{\dot\alpha}})$ is always negative, stability depends upon the sign of $C_{n_{p\alpha}}$ which may take on either sign. If $C_{n_{p\alpha}}$ is positive, then nutational stability depends upon the relative magnitudes of $K_T^{-2}(C_{m_q} + C_{m_{\dot\alpha}})$ and $K_A^{-2} C_{n_{p\alpha}}$. The pitch damping derivative is usually between an order to two orders of magnitude larger than $C_{n_{p\alpha}}$, but K_A^{-2} is about 30 times the size of K_T^{-2}. However, it would appear possible to stabilize most weapons in nutation at large spin rates.

The precessional mode usually presents the greatest difficulties in stabilization. Thus, as seen from expression (14), if the Magnus derivative is negative (Magnus center of pressure ahead of the center of gravity) the weapon will be unstable in precession. Furthermore, weapon stability is independent of the static pitching-moment derivative, C_{m_α}, which is the essential stability parameter

for a non-spinning body. This lack of dependence of stability upon C_{m_α} and, hence, of $\hat{\omega}_\alpha$, gives rise to the region F in Figure 12.

Basically region F indicates that beyond a certain spin rate there is the possibility (depending upon the sign and magnitude of $C_{n_{p\alpha}}$)

of either a nutational or precessional instability due to Magnus and that this instability is independent of the static pitching-moment derivative.

Finally, it may be seen from Figure 12 that if motion amplitudes, particularly in response to launch disturbances, are kept reasonably small (less than about 15 degrees), then two regions at B and C exist where satisfactory flight performance should be achieved. In region B the pitch rate is always higher than the roll rate and in region C the converse is true. It is important to note that as the lower left hand corner of both regions B and C is approached, fin alignments must be controlled to progressively smaller tolerances if the resonance region A is to be avoided.

The preceding discussion is concerned with the stability of symmetric weapons with fixed-cruciform stabilizers. The derived criteria are equally valid for weapons fitted with freely spinning stabilizers, provided the reduced spin rate, p, and the axial radius of gyration, K_A, refer to the stabilizer alone. In references 3 and 21 the concept of a freely spinning stabilizer was extended to bistable configurations with particular reference to the so-called monoplane tail. A detailed stability analysis for weapons using this type of stabilizer is given in reference 21.

A full understanding of missile dynamics is essential for successful weapon design. The occurrence of large amplitude oscillations in a free-fall unguided weapon can cause aircraft-weapon collisions, degrade performance by large increases in drag and affect weapon functioning. A second important consideration in weapon performance is the magnitude of the zero-lift drag.

Missile drag must be known for the preparation of aiming data and three basic techniques are commonly used to determine this important parameter; namely, wind-tunnel measurement, free-flight model tests and full-scale trials. When a weapon development program has progressed sufficiently to allow precise representation of the full-scale missile, wind-tunnel tests are required to give an accurate measurement of static stability. The importance of detailed reproduction of shape and excrescences at this stage was shown early in the Bomb Dynamics Program[1,13] Wind-tunnel testing initiated too early may lead to misleading results, followed by the need for expensive duplication of the work. Drag should be measured in these tests but need only be determined at discrete Mach numbers. To minimize the interference effects, wind-tunnel models are normally mounted from their base on a sting support. However, even with an arrangement of this kind, difficulty may be experienced if the missile has a significant boattail. In such cases the sting diameter required to withstand aerodynamic loads on the model may be virtually equal to the model's base diameter. The result is a distortion of the flow in the base region. Various semiempirical relationships are necessary to correct these measurements. These corrections are often troublesome to validate, particularly for transonic flow conditions.

The dependence of missile drag upon Mach number can be established in free flight by means of ground-launched rocket trials in which scale models are boosted to any desired maximum speed before being

allowed to separate and fall freely. Measurements of deceleration
and velocity of the model after separation from its boost motor
provide the necessary basic data. This is a quick and convenient
method which is appropriate to an early stage of a development program.
The experiment can be extended to include laterally fired, short-
duration rocket motors to disturb the model in flight and, hence,
provide a technique for determining dynamic-stability derivatives.
These latter measurements should be confirmed at a later stage under
the more controlled conditions of wind-tunnel tests.

The last part of a ballistic design exercise consists of free-
fall drops of early production or preproduction rounds from which
drag would be measured on a sample of stores in order to confirm
earlier measurements and give an estimate of consistency. All
three techniques outlined above have been used to measure drag on a
particular bomb (see Figure 13). The results of these measurements
are given in Figure 14.

5.3 A Practical Example of Bomb Design

To indicate how various testing techniques may be applied to
problems in bomb design, the following example is drawn from recent
development of the bomb which is illustrated in Figure 13. Initial
studies of this bomb were based on an earlier design for which some
wind-tunnel data were available; these data were used to predict
fin size and center-of-gravity positions. However, during engineering
development of the weapon, certain changes were made which necessi-
tated an increase in centerbody length, a growth in tail cone base
diameter and a limitation imposed on fin span. The use of
retractable fins on this bomb was not acceptable to the weapon designer.

When details of the basic configuration had been agreed to, it
became important to perform six-component wind-tunnel tests on a
model. The largest possible model scale was chosen to give confidence
in results for incidence angles up to 30 degrees. The data from these
wind-tunnel tests were fairly typical for a cruciform bomb.[26]
However, there was evidence of static instability at small angles of
attack at transonic speeds and low static stability at all speeds.
Having obtained detailed aerodynamic data on the store, computer
studies were then initiated to predict the likely performance of the
weapon and to assess requirements for the manufacturing tolerances.
It should be emphasized here how modern computing facilities have
contributed most significantly to the analysis of problems in
ballistics. It is now commonplace to solve the equations of motion
of a rigid body having six degrees of freedom and subject to a
position and rate of change of position dependent system of external
aerodynamic forces and moments. Computer programs are currently
available to handle problems with widely varying complexity. The
works of Holmes[8] and Goodale[9] were used extensively in the Bomb
Dynamics Program.

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[26]Fellows, K. A., "Some Results of Force and Pressure Plotting Tests
on a Symmetrical Store," ARA Model Test Note 546/2
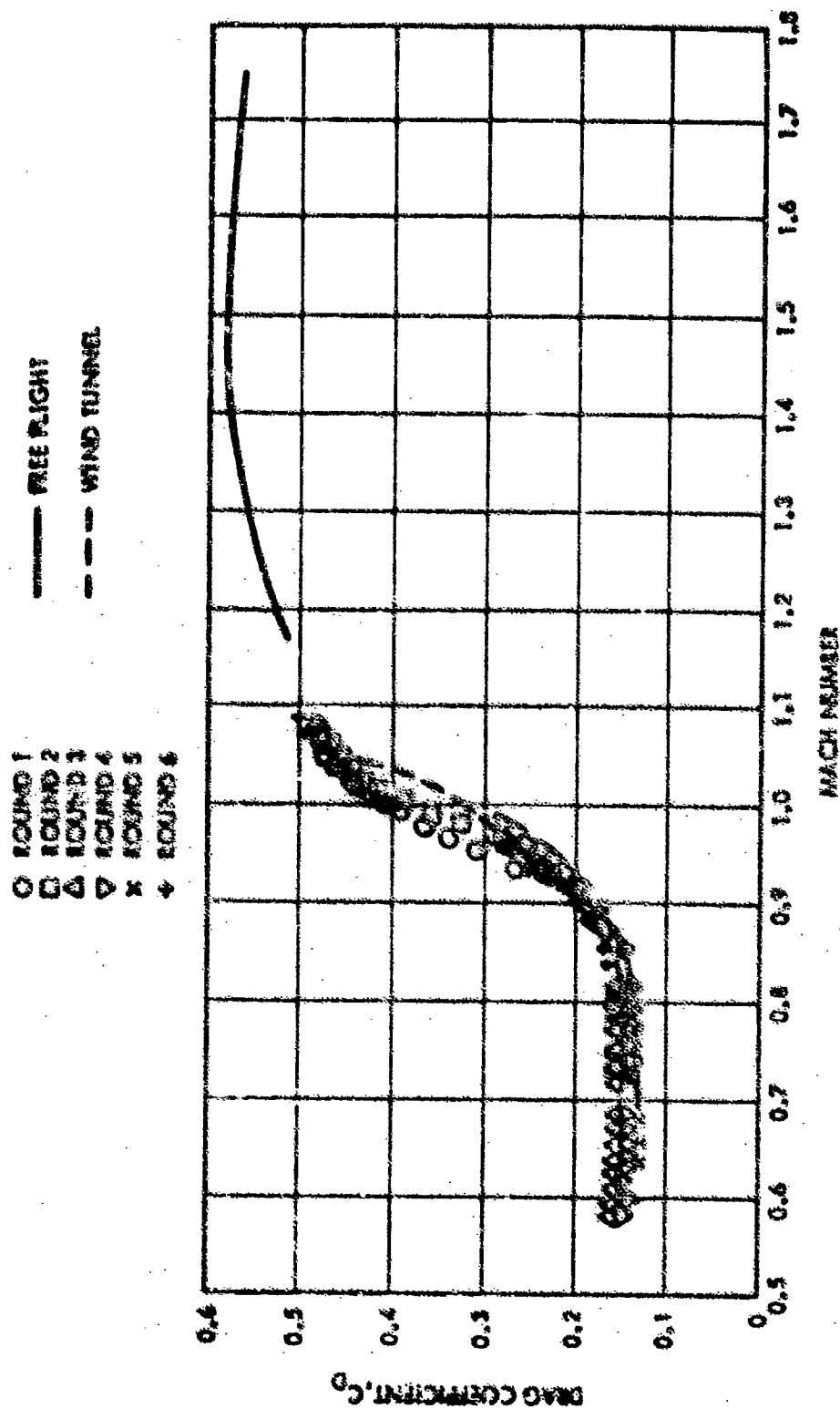
FIG. 13 REFERENCE BOMB

FIG. 16 DRAG COEFFICIENT VERSUS MACH NUMBER FOR THE REFERENCE BOMB

For the reference bomb, two types of computation were performed. The first, which might be termed a "catastrophic yaw search," comprised a number of predictions representing three seconds of flight from release. Mach number and release height were varied to cover the operational range of the weapon and systematic changes were included for center-of-gravity position, fin cant and initial roll orientation. Due to flow deflection in bomb bays and outwash effect on pylon-carried bombs, the initial roll orientation of the angle-of-attack plane cannot be readily determined. This follows from the fact that the measurement of the flow characteristics for the required multiplicity of aircraft and weapon characteristics is quite prohibitive. Even by restricting the combinations of variables to include only the more critical situations, it was found necessary to examine between two and three hundred cases for the bomb under consideration. For ease of interpretation, complex yaw plots were produced for each case; systematic changes were noted and danger areas were identified for the range of parameters. Illustrations of examples of these plots are shown in Figures 15 and 16. The second type of computation, which could be described as a "resonance search," made use of the computer program to predict flight histories of the ratio of the pitch-to-spin frequency for a range of representative release conditions. From these records it was a simple matter to deduce, for each center-of-gravity position, a limiting fin cant which would always maintain the spin-to-pitch frequency below resonanc With results obtained from these computer studies it was possible to specify an envelope of maximum allowable release disturbance center-of-gravity shift and fin manufacturing tolerance.

On the basis of predictions from the "catastrophic yaw search" and the "resonance search," it was established that, for a maximum release disturbance of 20 degrees, the fin cant should not exceed a value of approximately 0.05 degree. This figure was determined primarily by the fact that limitations on fin span produced a weapon with low static stability and correspondingly low natural pitching frequency. Accordingly, to avoid both resonance and adverse release disturbance effects, the most suitable design criterion was to maintain roll rates below the pitching frequency (that is, design for the lower left-hand corner of region B shown in Figure 12). To maintain a tolerance of such small magnitude, it was necessary to submit fins of preproduction rounds to searching examination. A computer program was therefore prepared to make use of 33 measurements over each fin surface so that airfoil theory could be applied, taking account of fin cant, camber and twist to determine an effective mean fin-cant angle for the tail.[27] These mean fin-cant angles were subsequently compared with equivalent mean fin-cant angles derived from the roll histories of the free-flight full-scale trials. The results, shown in Figure 17, exhibited a discouraging lack of correlation, but did indicate that the roll tolerance was being easily met. The lack of correlation is thought to be due to roll

[27]Smith, K. G., "A Method for Estimating the Cant on Fin Zero Lift Angle Accidently Built into a Missile During Manufacture," Hunting Engineering, Ltd., Tech. Memo HE/TM/77/177, February 1964
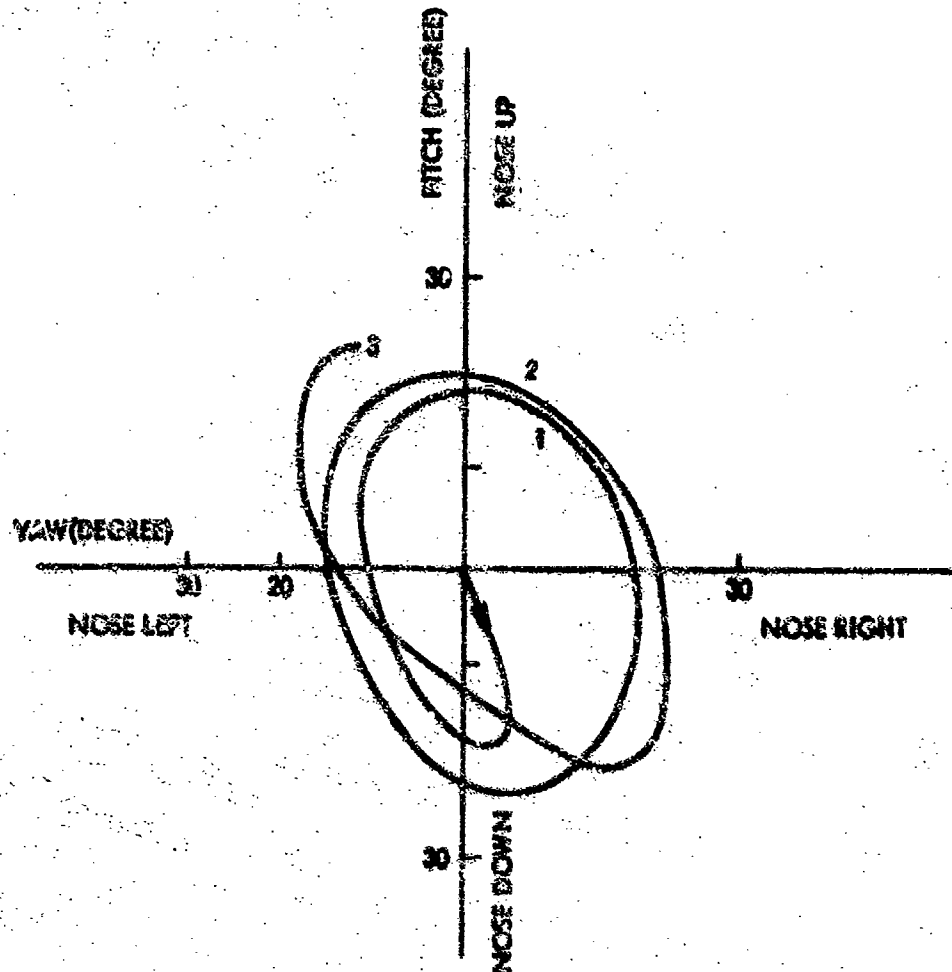
FIG. 15   RESPONSE TO 20-DEGREE RELEASE DISTURBANCE, 202-DEGREE ROLL ORIENTATION AND A 0.03-DEGREE FIN MISALIGNMENT IN ROLL
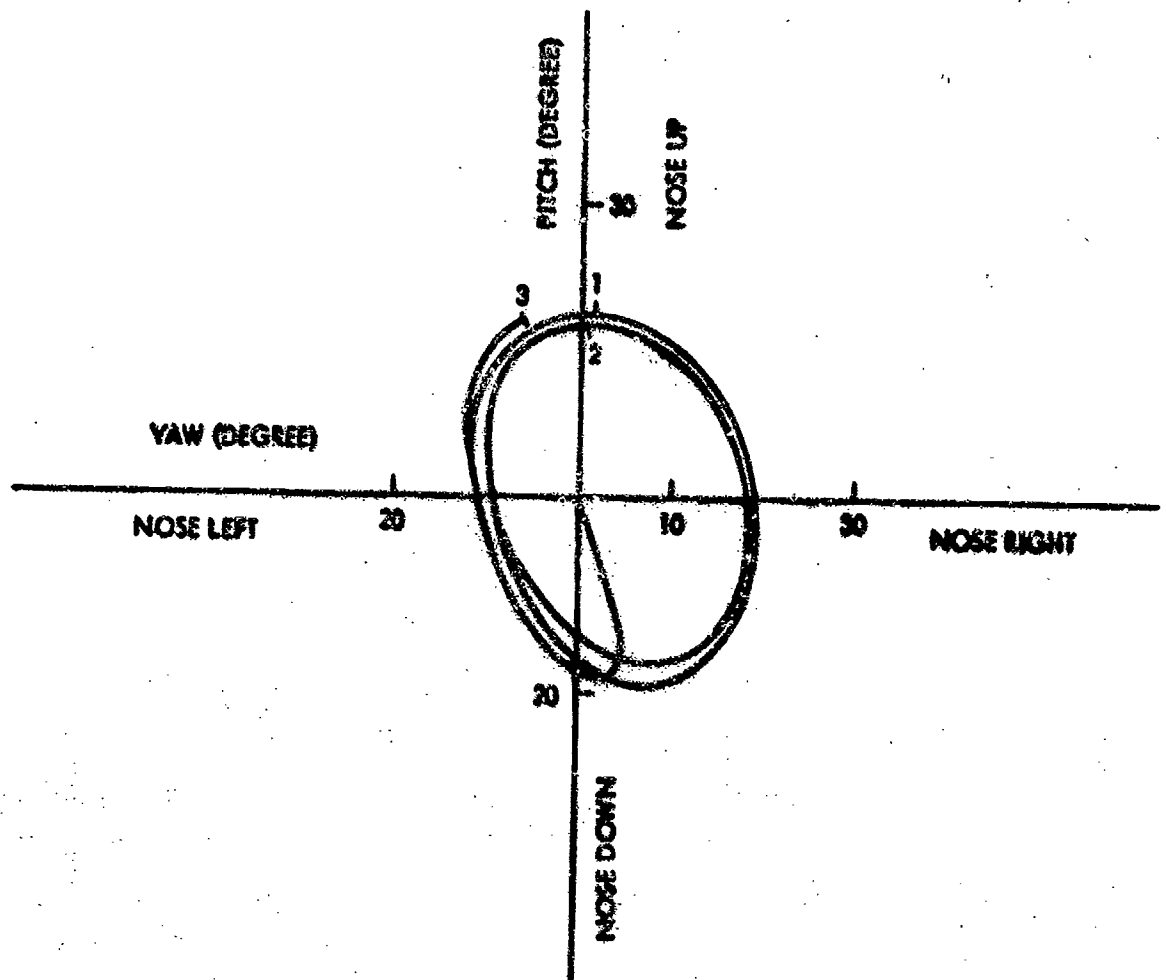
FIG. 16 RESPONSE TO 20-DEGREE RELEASE DISTURBANCE, 202-DEGREE ROLL ORIENTATION AND A 0.1-DEGREE FIN MISALIGNMENT IN ROLL
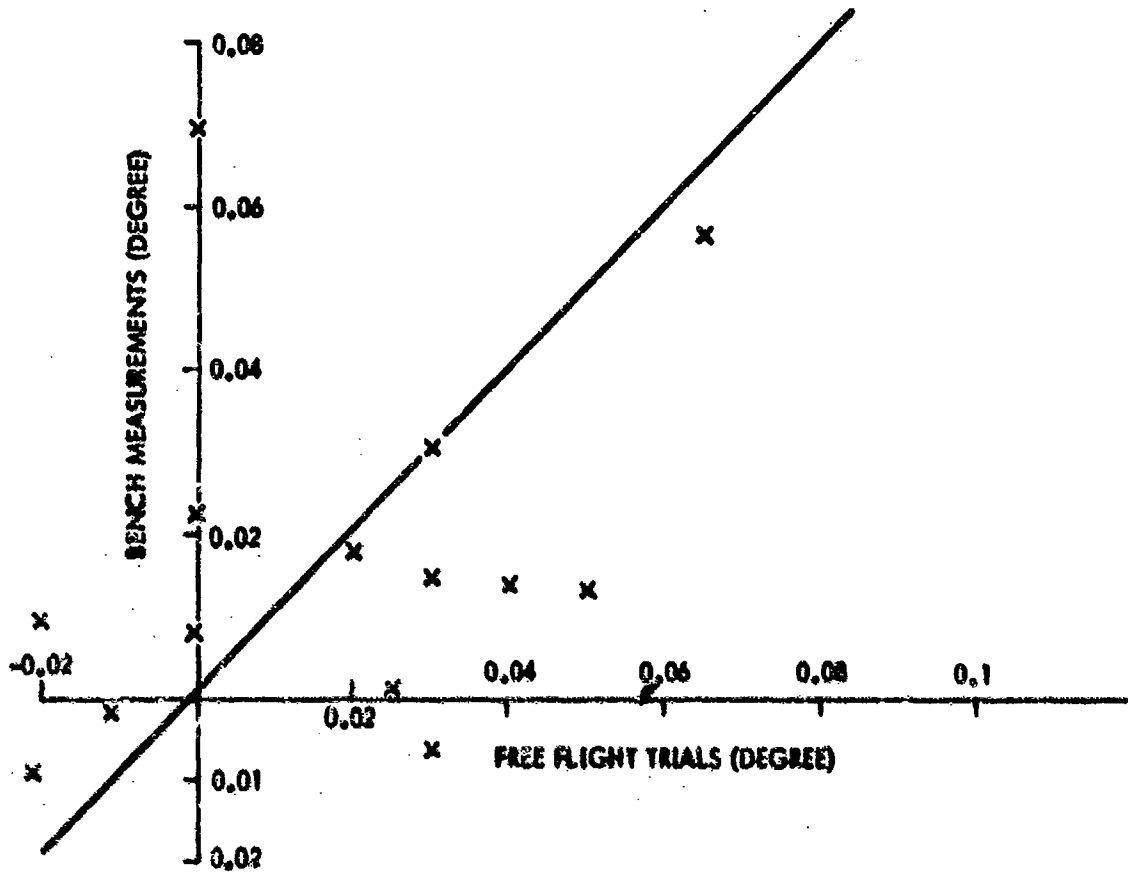
FIG. 17 COMPARISON OF FIN MISALIGNMENT MEASUREMENTS

induced by body asymmetries and to the difficulty of measuring the fins to the accuracy required for the computer program. However, since the method could clearly detect fin misalignment at the tolerance rejection level, the computer program was adopted as a standard production inspection tool.

6.0 CONCLUSION

A primary objective of the joint WOL/RAE/WRE research program on bomb dynamics has been to demonstrate the feasibility of predicting free-fall weapon performance on the basis of motion simulations using relevant aerodynamic data as measured in wind tunnels in conjunction with digital computing techniques. In general, the predicted motions of the bomb test vehicle have shown a high degree of correlation with the observed flight histories, although, as might be expected, complete equivalence was never achieved. It was, therefore, demonstrated that wind-tunnel tests of precisely similar models can yield data which may be used with confidence to predict full-scale missile behavior. A significant result of the research has been insight acquired on the importance of yaw-induced forces and moments in contributing to the stability of streamlined missiles and the sensitivity of these forces and moments to small configurational changes.[13]

With reference to the fixed-cruciform finned bomb, new techniques of design have been established, making use of wind tunnel and free-flight tests which are supported by comprehensive ballistic performance studies carried out on high-speed computing facilities. Such methods have been shown to highlight the effects of poor design at an early stage in weapon development and to provide a reliable means for the assessment of ballistic consistency.

The experiments with unconventional stabilizers[2,3] have shown that freely spinning cruciform tails fitted to a bomb eliminate the induced rolling moment and diminish the induced yawing moment and side force. Thus, it should be possible to lower the static-stability boundaries. If suitable engineering designs can be found for the bearings, then the spinning stabilizer will provide an attractive solution for many freely falling weapons. However, it was also shown that the split-skirt does not offer a simple solution to the stability problems. With unflanged surfaces this stabilizer is not free from adverse effects induced by yaw and the use of flanged-skirt segments gives only a modest improvement in performance.

Throughout the research program, wind-tunnel facilities in the United Kingdom, United States and Australia were used to produce the required aerodynamic data. Comparisons of these data, which were based on identically similar models, provided a most effective means for checking the results because the various wind tunnels had widely differing capabilities. Particularly interesting correlations of dynamic measuring methods were made possible with data from "free oscillation" tests in the United States and "forced oscillation"

tests in the United Kingdom. In general, the results showed good agreement and were confirmed by full-scale measurements made in the free-flight trials.

Concerning overall supervision of the program, there is no doubt that communication difficulties contributed to a rather prolonged time scale. In consequence, the working teams did experience difficulty in maintaining their level of effort under the conflicting prioriites of other tasks. Although formal reporting of the results has been kept up-to-date through meetings such as TTCP, documentation of the work has been seriously delayed. However, it should be emphasized that a number of factors contributed to successful cooperation in carrying out the research, creating a vital and cohesive influence throughout, which did much to extend the scope and depth of the work undertaken.

Thus, meetings at working level were convened on an average at yearly intervals to discuss the technical problems and report progress. On such occasions overseas travel was minimized by limiting participation to only those people who were working directly on the research. Specific objectives were set for the research teams of each country by experts in exterior ballistics who met at special symposia or at meetings of the Exterior Ballistics Panel (07) of The Technical Cooperative Program (TTCP). Furthermore, in planning the program of activities, consideration was given to the talents and facilities available in each country so that the overall effort could be directed to obtain the greatest possible advantage.

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